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HOME ENERGY MANAGEMENT SYSTEM SOLUTIONS FOR THE EUROPEAN GRID

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ABSTRACT

Since several years, home energy management has been gaining significance in Europe. The increasing share of decentralized fluctuating renewable energy generation, mainly from PV, calls for activation of flexibility at the demand side. Home energy management systems (HEMS) could be a key component to activate such flexibility and are expected to represent a substantially growing market segment in the next few years.

The paper at hand proposes a definition for the term HEMS and its differentiation from neighbouring fields in the smart home sector. A summary of commonly known drivers and barriers is given and a generalized abstract look at HEMS is taken. Appropriate market-available or near market-available HEMS solutions in Europe are anonymously listed and compared, especially focusing on information and communication technology (ICT) aspects. Finally, OGEMA 2.0 is presented as a software standard for residential energy management gateways.

1 INTRODUCTION

Since several years, home energy management has been gaining significance in Europe due to various reasons. Increasing share of decentralized fluctuating renewable energy generation (mainly from PV) calls for activation of flexibility at the demand side. Also, rising energy prices and a rapidly developing technology in the area of embedded ICT and small automation solutions form the base for new business models. A number of studies are predicting the smart home market to substantially grow in the next few years (cp. Table 1). The European Joint Research Centre [1] counts over 145 EU smart grid projects focusing on smart customers – most of them on the residential sector. These figures highlight a substantial degree of attention to the overall topic.

Table 1: *Estimations of future home automation market size by various sources*

Source	*Region*	*Market value [Billion USD]*	*By year*
Marketsandmarkets 2013 [2]	Global	51.77	2020
Greentechmedia 2013 [3]	Global	1.5	2013
Grand View Research 2014 [4]	Global	47.61	2020
Strategy Analytics 2014 [5]	Global	115	2019
Marketsandmarkets 2013 [6]	USA	22.4	2020
Forbes 2014 [7]	USA	7.8	2019
Marketsandmarkets 2013 [8]	EU	13.81	2020
Deloitte 2013 [9]	EU	4.1	2017

1.1 Definition of smart home energy management

In general, energy management includes planning and operation of energy generating and consuming units. The VDI-Guideline 4602 released a definition which includes the economic dimension: "Energy management is the proactive, organized and systematic coordination of procurement, conversion, distribution and use of energy to meet the requirements, taking into account environmental and economic objectives" [10]. In the sector of Home Energy Management, also social aspects seem important [11].

The term "Smart Home" is a keyword oftentimes used in conjunction or confused with HEM. A commonly accepted general definition for this term seems to be missing. [12] defines that a smart home is a privately used residential area where various devices of home automation (e.g. room heating, lighting, ventilation), household appliances (e.g. fridge, washing machine), consumer electronics and communication devices become intelligent goods which are oriented towards the inhabitant's needs. By interconnecting those goods, new assistance functions and services which generate a surplus value exceeding the individual use of the appliances are provided to the inhabitants.

The German standardization roadmap Smart Home & Building [13] states that a Smart Home comprises privately used residential living and office areas where (1) the needs of the inhabitants are assessed by a plurality of sensors and smart devices allowing for intuitive control, (2) assessed information is processed with regards to the current state and anticipation of future states and (3) action follows upon the assessed information and the interpretation thereof. The action is implemented by means of a connected home network enabling for simple and secure coordination of consumer electronics, information and communication technology, electric household appliances and building technology (alarm systems, heating- and lighting-control etc.) using interfaces, software etc. by means of wired or wireless technologies. It is stated that private persons are in the focus of the smart home, whereas the term "smart building" focuses on the (commercially used) building.

Hence, the understanding of the term "Smart Home" is not at all limited to HEM. In [13], Energy management, entertainment, ambient assisted living and smart home infrastructure/automation are all understood as domains of the smart home market. Services towards home inhabitants arise according to these domains. Commonly known further services include Lighting, Heating, Ventilation & Air Conditioning, Energy Generation, Home Security & Surveillance, Safety (gas/water/fire detection) and Household Appliance Supervision & Control.

A combination of energy management and smart home definitions yields a description of HEM(S): *Home Energy Management (HEM) is the proactive, organized and systematic coordination of procurement, conversion, distribution and use of energy within a privately used residential area with the goal of providing services and meeting requirements of the inhabitants, taking into account environmental, economic and social objectives. Home Energy Management Systems (HEMS) are technological means designed for the implementation of HEM.*

1.2 Differentiation to neighbouring fields

It seems that part of the confusion about the Smart Home Domain arises because there are many overlapping sub-domains. Figure 1 is a proposal for the differentiation of these domains and neighbouring fields. Herein, HEM is considered a sub-domain of home automation, which again is a sub-domain of the smart home. The domain of "next generation media" [14] or "pervasive computing" crosses the smart home boundary and has quite a big range of influence into the other three domains. As seen from the figure, all fields are highly interdependent.

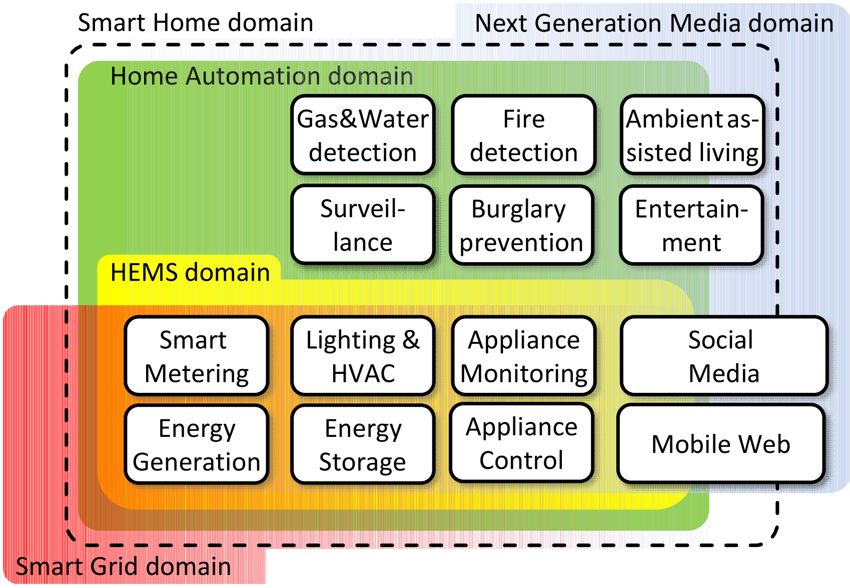

Figure 1: *Home energy management neighboring fields and domains.*

1.3 Home energy management goals

Home energy management comprises various organizational and technical aspects of efficient energy usage in private households, which can be grouped as follows:

- Energy management aiming at shifting energy consumption or generation in time with the aim to balance generation and consumption. This may be achieved by means of energy storage. However, when considering electric energy, storage is expensive and usually only of limited availability. Hence, shifting the time-of-use of appliances is an interesting alternative here. For economic reasons, the most important use case in this context is the shifting of load operation in order to increase self-consumption of generation from photovoltaics. Relevant loads with high flexibility potentials are heat pumps and electrical vehicles. Operation of a battery may still be included.
- Energy management aiming to reduce energy consumption via adaption of device operation. The most important area of application for this purpose is room heating and cooling. In many European countries residential heating largely relies on burning fossil fuels (mainly oil and gas), sometimes combined with district heating systems. In southern Europe, electric heating and cooling offers energy efficiency potentials, too. Efficiency measures comprise temperature adaptions of rooms and/or buildings in

times when they are not used in order to reduce energy losses to the outside and switching off components of the heating system when possible in order to reduce stand-by losses.

- Efficiency of other devices in households, e.g. standby losses, is usually focused on device design. Such energy efficiency measures are also important for overall energy efficiency, but are considered outside the scope of energy management in this work.
- Energy management aiming to optimize energy efficiency of buildings taking into account investment into the building such as exchanging heat burners, windows, improving insulation and installation of a photovoltaics/ thermal solar plant. In the context of building and facility management this is also sometimes considered as part of energy management, but is outside the scope of this work which is focusing on automized operation measures rather than building refurbishment.

Compared to energy management in the commercial and industrial environment, home energy management faces several extra challenges, of which economic aspects and user acceptance are the most important ones. Due to small scale of energy systems and energy turnover in private households systems, solutions have to be very cost efficient, robust with regards to use by non-experts, and must allow to be standardized as mass products. User acceptance requires intuitive usage and/or fully automated operation. Bothering the user with energy management decisions is not feasible for most use cases, while at the same time user requirements and preferences have to be taken into account when performing energy management influencing device operation [15][16].

1.4 Drivers and barriers

Because of HEMS being a sub-domain of the smart home with highly interdependent fields, many incentives and barriers to the smart home also apply to HEMS. First of course, there are strong policy drivers at national and European level which favour introduction of HEMS for energy efficiency and sustainability increase. Furthermore, Figure 1 indicates that main drivers to HEMS may come from the emergence of next generation media and the smart grid.

HEMS are a potential element of smart grids as they enable active integration of residential loads (“demand side integration”) and generators, or at least improve conformity of residential distributed energy resources to (smart) grid requirements (e.g. electric network driven deration of photovoltaic generators). This may reduce the need for network expansion and improve the networks tolerance for integration of renewables. The recently published study on distribution networks [17] encourages management of distributed generation in the low-voltage grid, for which it foresees high grid cost reduction potentials. Demand side management, on the other hand, is discouraged as the resulting cost reductions are considered very small.

Next generation media [14] are actively used by smart home residents in their daily life. A commonly known main incentive regarding HEMS is energy cost reduction, which seems somehow controversial since the introduction of smart home devices gives rise to investment cost. Other drivers oftentimes found are quality of life improvement, contribution to environment protection, improving the home's energy self-sufficiency and enhancing transparency [19]. Finally, favourable policies and regulatory incentives are major drivers.

Taking a look at the barriers, we first find the cost of HEMS solutions, breaking down into investment and running expenses (e.g. subscription fees). Technical barriers oftentimes found [18][19] include:

- Lack of an advanced smart metering infrastructure
- Lack of smart appliances on the market,
- Lack of mass-scale roll-out of "Home area automation controllers"
- Lack of interoperability between smart home and ICT systems of smart grid market actors such as distribution system operator, virtual power plant and market aggregators, e.g. for enabling automatic energy procurement by the end customer.
- Lack of interoperability between solutions from different manufacturers
- Poor usability and lack of plug-and-play like integration ability of new smart home appliances or distributed generators into the smart grid system involving all market actors.
- Lack of commonly accepted and robust solutions for data security providing guaranteed confidentiality, integrity and availability for information transfer between end user and all market actors
- Lack of appropriate standards considering all aspects mentioned above

Non-technical barriers include:

- Threat to privacy of customers
- Lack of understanding of smart home technical aspects by end users, general disinterest
- Loss of end-user control and freedom of decision
- Lack of trust in energy companies and government
- Lack of or unfavourable regulatory conditions
- Unfavourable political conditions

2 COMPARISION METHODOLOGY

2.1 Abstract view on Home Energy Management Systems

Despite the fact that there is a large number of various HEMS on the market today, common basic component classes may still be identified. This is the case for both hardware and software components. Hence, a generalized abstract view of HEMS components can be developed which is shown in Figure 2. The figure attributes components to component levels.

Taking a look at the figure's bottom, at the device level we find stand-alone sensor and actor devices of various kinds. Examples for this would be a motion detector or a roller shutter motor. A complex sensor/actor would bundle several sensors and/or actors into one, e.g. an electronic power plug capable of switching a lamp while measuring its power at the same time. Finally, a complex device would represent an appliance containing sensors, actors and a controller of some kind, for example a room thermostat (containing a temperature sensor and a two-point controller in the simplest case) or an electric vehicle (eventually containing a complex sensor network and a charging controller). Also, simple controller-equipped devices (e.g. a freezer) combined with a complex sensor/actor device may represent a complex device if seen as single appliance.

Devices as such may be mapped onto the sensor/actor level where we merely find single data points. Typical sensor classes on this level include measurement of power consumption/generation, use of energy, metering, occupancy, brightness level, and temperatures. Actors typically influence energy related processes, e.g. bi-stable or multi-state electric switches, dimmers or motors. They are connected by a sensor/actor network which might use various kinds of communication technologies and protocols, thus forming a heterogeneous network containing bridges and/or protocol converters, e.g. a ZigBee / Ethernet converter.

The sensor/actor network level connects to a central computing system which will be called "gateway" for further reference. The basic functions of the gateway are monitoring, data acquisition and recording of the sensor values as well as implementing control of the actors depending on sensor values, user requests and external smart grid information.

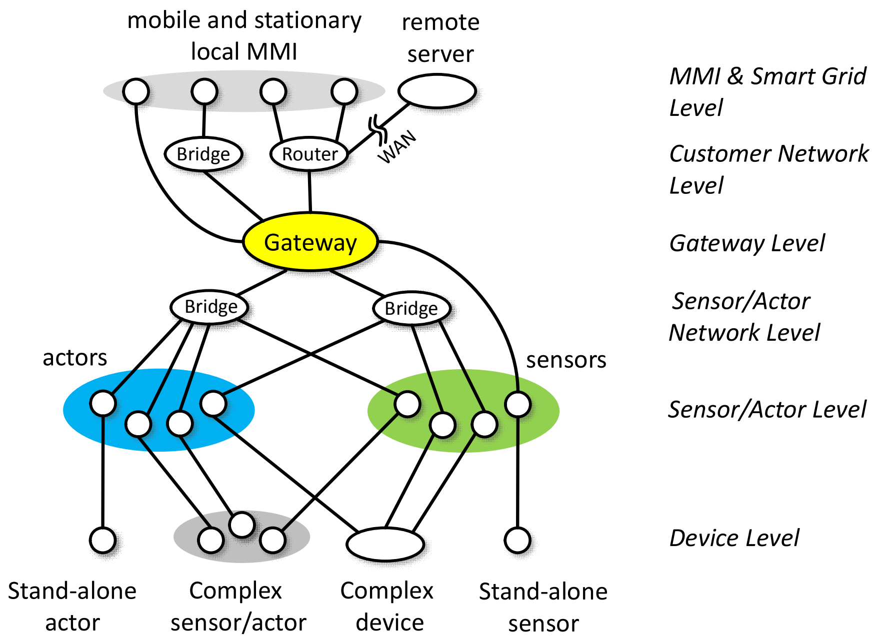

Figure 2: *Generic HEMS component scheme.*

There is a customer network level which connects the gateway to man-machine interfaces operated by the users (typically the residents) as well as smart grid participants accessing the system from remote (e.g. distribution system operators). It shall be noted that the customer network level features a heterogeneous network, e.g. using LAN and WLAN, any may or may not share network infrastructure with the sensor/actor network level. A USB-WLAN stick or a DSL Internet Router may eventually resemble bridges in the customer network level and sensor/actor level at the same time.

The man-machine interface (MMI) at the topmost level may include any interface accessed by the residential customers including mobile and stationary solutions, ranging from simple switches up to web-based graphic user interfaces.

Software now is present at most of the levels, ranging from MMI client software, e.g. an internet browser, over the gateway operating system down to device level embedded system firmware. Taking a closer look at the gateway being a central HEMS component, we typically find a software stack as depicted in Figure 3. A practical example for such stack would be Linux as operating system, driver and hardware abstraction, a JAVA virtual machine, OSGi as service delivery platform, OGEMA as middleware (cp. Section 4), and an energy consumption monitoring application with web-based user interface.

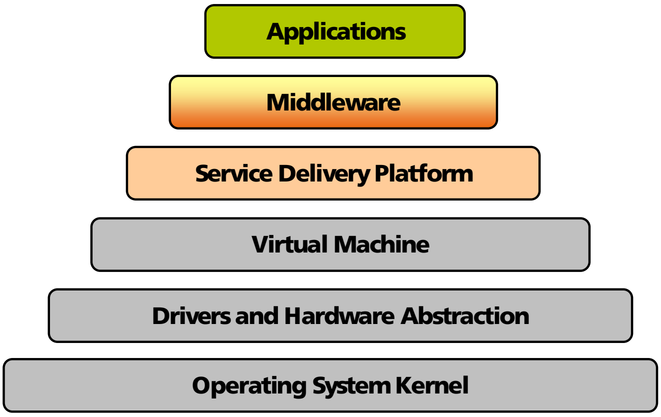

Figure 3: *Generic smart home gateway software stack.*

2.2 Social aspects and gamification

The major goals of energy management as described in Section 1.3 focus on efficient usage of energy, which usually results in a cost reduction of the energy billed to the user / operator of the building or private household. Hence, monetary incentive for installation and operation of energy management systems traditionally is decisive, sometimes combined with aspects of reducing environmental impacts of energy consumption. However, especially for private households, the monetary incentives are typically insufficient to trigger investment and interest in dealing with additional technology.

An up to now less developed approach to HEMS are incentive systems which do not primarily work on monetary basis, but focus on intrinsic user motivation. An appropriate approach is known from game design as "gamification" meaning „use of design elements characteristic for games in non-game contexts" [21] and "enrichment of products, services and information systems by game elements with the goal of positively influencing motivation, productivity and behavior of users" [20, 21].

An overview of different kinds of games or gaming applications summarized by the general term „ludification" is shown in Figure 4. Gamification represents an individual concept amongst others in the context of ludification, e.g. serious games, simulation & training games or playful interaction.

Where other incentive mechanisms are typically based on increasing extrinsic motivation which is oftentimes subject to habituation resulting in only short-living effects, gamification is aiming at "increasing the intrinsic usage motivation" and its effects base on "extensive motivation support" [20, 22].

McGonigal [20, 22] names the following motivation supports:

- Increase of satisfaction
- Mediate of optimism
- Enable social interaction
- Mediate of importance
- Change of behaviors
- Support of learning processes

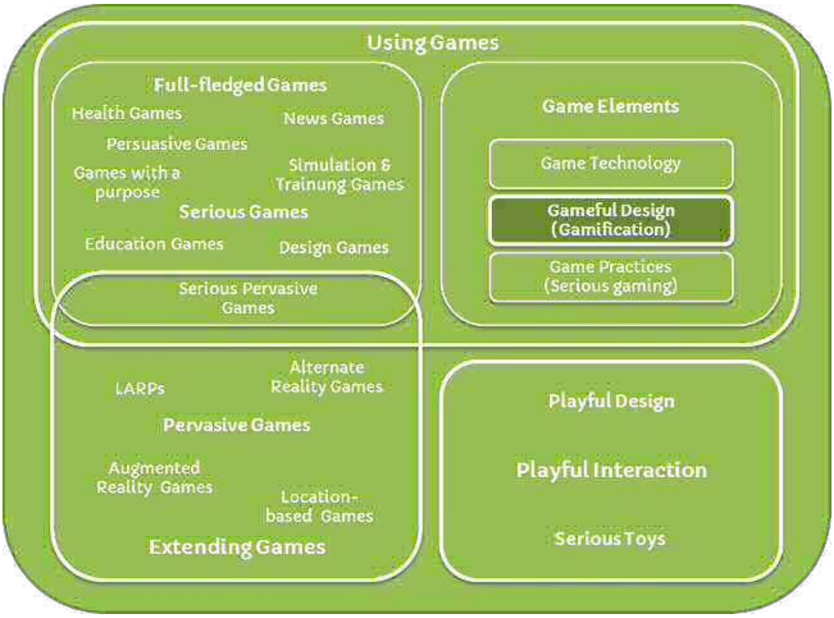

Figure 4: *Ludification.*

Table 2 lists levels of game design elements according to Deterding et al. [21], their differences and according examples. In the context of HEMS, suitable elements have to be related to user motives.

For example, an individual user's achievements can be rewarded by aggregation of game points. By networking of users and introduction of rankings, competition and social status can be addressed as a motive, promoting interaction within the user community. The resulting dynamics may be beneficial for the emergence of a technically and socially optimized, balanced and sustainable energy system.

Table 2: *Levels of Game Design Elements*

Level	***Description***	***Example***
Game interface design patterns	Common, successful interaction design components and design solutions for a known problem in a context, including prototypical implementation	Badge, leaderboard, level
Game design patterns and mechanics	Commonly reoccurring parts of the design of a game that concern gameplay	Time constraint, limited resources, turns
Game design principles and heuristics	Evaluative guidelines to approach a design problem or analyze a given design solution	Enduring play, clear goals, variety of game styles
Game models	Conceptual models of the components of games or game experience	MDA; challenge, fantasy, curiosity; game design atoms; CEGE
Game design methods	Game design-specific practices and processes	Playtesting, playcentric design, value conscious game design

Table 3: *HEMS product classes*

Nr	*Product Class*	*Focused Levels (cp. Figure 2)*
A1	Retrofitting systems with broad range of application and extendability, which are not limited to energy management, but cover various home automation applications. Radio communication based Sensor/Actor Network level, typically do-it-yourself installation by end users.	Sensor/Actor, Sensor/Actor Network, Gateway, MMI
A2	Retrofitting systems with limited range of application and few extendability options. Radio communication based Sensor/Actor Network level. Do-it-yourself installation possible, but professional installation recommended.	Sensor/Actor, Sensor/Actor Network, Gateway, MMI
A3	Retrofitting systems with strong focus on a single application and no extendability options. Closed systems. Radio communication based Sensor/Actor Network level. Do-it-yourself installation possible, but professional installation strongly recommended.	Sensor/Actor, Sensor/Actor Network, Gateway, MMI
A4	Systems for initial equipment and extensive refurbishments. Typically cable based Sensor/Actor network level. Professional installation necessary or strongly recommended. Usually these systems are not limited to energy management, but also cover other home automation applications.	Sensor/Actor, Sensor/Actor Network, Gateway, MMI
A5	Frameworks, Integration solutions etc. as basis/module for HEMS or general home automation solutions or products	Gateway

2.3 Basis of system comparison

The goal of comparing HEMS systems or system components calls for an according methodology. Generally, it is possible to compare hardware or software aspects of the different system levels. Also, distinct product classes can be defined as summarized in Table 3.

The list of barriers as described in Section 1.4 as well as the technical characteristics described in Section 2.1 can be used to derive general, non-technical and technical comparison aspects which might refer to one or more product classes. They are summarized in Table 4, Table 6 and Table 5. In these tables, the bold text refers to keywords used in the comparison lists in Section 3

Table 4: *General comparison aspects*

Comparison aspect	***Product Class Nr.***
What is the **aim** of the solution (e.g. monitoring, energy efficiency enhancement etc.)?	All
Which **product class** does the solution belong to? Is it focused on a specific HEMS level?	All
Which **energy type** is considered (electric and/or thermal)?	All
What is the **status** of development (commercial, R&D project etc.)?	All

Table 5: *Non-technical comparison aspects*

Comparison aspect	***Product Class Nr.***
What is the **investment cost** for a basic system including gateway and two simple sensor/actor devices (thermostats unless otherwise noted)?	All
What is the **running cost** per year?	All

Table 6: *Technical comparison aspects*

Comparison aspect	*Product Class Nr.*
Does the sensor/actor network level rely on **wired or radio** communication? Are multiple technologies supported or does the product define an own one?	A1-A4
Which **standard conformity** is provided? Does the solution define a standard on its own?	All
Does the solution provide an advanced programming interface (**API**)?	A1, A2
Does the solution software provide an **application runtime environment**?	All except A3
Is Do-it-yourself (**DIY**) installation supported?	All except A4
Is a solution specific **online social community** present?	All
Is there a system specific **online blog**?	All
Does the solution implement a **gamification** approach?	All
Is there a **smart grid interface** for ICT connection towards market actors?	All
Does the solution provide a **metering interface** for connection to a billing relevant smart meter infrastructure?	All
Is there an **online software store** for purchasing extensions or upgrades?	A1, A2
Is there specific **developer support**?	A1, A2
Does the solution base on **open-source** software?	All except A3
Is **user access** to / interaction with the system possible when it is offline (no internet connection), or does operation and user interaction rely on the system being online?	All
MMI options: is there a **smart phone interface** offered?	All
Is the use of specific **data security technologies** advertized towards the user?	All

3 OVERVIEW OF SYSTEM SOLUTIONS

3.1 Solution list and comparison outcome

This section lists comparison outcomes for A1-A4 class solutions. As shown in the following Tables 7-10, there is a high number of according commercial products. The table columns refer to selected comparison aspects as defined in Section 2.

Investment costs are not given in absolute numbers because solutions often are hardly comparable. Instead, the cost range for a basic system is specified, where "low" would represent anything up to 300 €, "medium" up to 700 € and "high" anything above. These numbers are referring to a very basic typical setup and may go up for larger installations in all cases, of course. As there is an extreme variety of products, many of them focused to only certain national markets, this cannot be considered a complete list, but a provision of an overview what kind of systems are offered at the time of investigation.

The table column "Wired/Radio" refers to the sensor/actor network level communication system. The tables use the following abbreviations:

IF	Interface
EE	Energy Efficiency
HA	Home Automation
G	General
E	Electric
T	Thermal
C	Commercial
A	Announced
R&D	Research & Development Project
Cty	Community driven
R	Radio Communication
W	Wired Communication
Y,N,P	Yes, No, Partly
SOTA	State of the art

Please note that all information is given based on public vendor / reseller information. For explanation of the keywords used in the columns, please refer to Table 4, Table 6 and Table 5.

Table 7: *HEMS systems*

Product Nr.	Aim	Product Class	Energy Type	Status	Investment Cost	Running cost [€/a]	Wired/Radio	Standard Conformity	API	App Runtime Env.	DIY support	Online community	Blog	Gamification	Smart Grid interface	Metering Interface	Online software store	Developer support	Open Source	User Access	Smart Phone IF	Data security techno-logies
1	EE, HA	A1	G	C	low	-	R	ZigBee	1	N	Y	Y	N	N	N	N	N	N	N	online	Y	AES256 CBC, TPM Spec. 1.2
2	EE, HA	A1	G	C	low	-	R	N	1	N	Y	N	N	N	N	Y	N	N	N	online	Y	SOTA
3	EE, HA	A1	G	C	low	-	R	N	P	N	Y	N	N	N	N	Y	N	P	N	both	Y	AES
4	EE	A2	T	C	med	-	R	N	-	N	P	N	N	N	N	N	N	N	N	offline	N	-
5	EE	A2	T	C	low	-	R	N	-	N	P	N	Y	N	N	N	N	N	N	online	Y	SOTA
6	EE	A2	T	C	med	-	R	N	-	N	P	N	N	N	N	N	N	N	N	both	Y	?
7	EE, HA	A1	G	C	med	59	R	Z-Wave	Y	N	Y	Y	N	N	N	Y	N	N	Y	online	Y	SOTA
8	EE, HA	A1	G	C	med	-	R,W	misc.	-	N	P	N	Y	N	N	Y	N	N	N	both	Y	SOTA
9	EE	A2	T	C	low	-	R	N	-	N	Y	N	N	N	N	N	N	N	N	both	Y	AES128
10	EE, HA	A3	G	C	high	-	W	KNX	-	N	N	-	-	-	-	-	-	-	-	both	Y	-

1: only for selected partners

***Table 8:** HEMS systems (continued)*

Product Nr.	***Aim***	***Product Class***	***Energy Type***	***Status***	***Investment Cost [€]***	***Running cost [€/a]***	***Wired/Radio***	***Standard Conformity***	***API***	***App Runtime Env.***	***DIY support***	***Online community***	***Blog***	***Gamification***	***Smart Grid interface***	***Metering Interface***	***Online software store***	***Developer support***	***Open Source***	***User Access***	***Smart Phone IF***	***Data security technologies***
11	HA	A2	G	C	high	-	R	KNX/EIB	-	N	N	N	N	N	N	N	N	N	N	both	Y	-
12	[1]	A1	G	C	med	-	R	EnOcean	-	N	Y	N	N	N	N	N	N	N	N	both	Y	SOTA
13[3]	HA	A1	G	C[2]	?	?	R,W	misc.	?	?	Y	N	N	N	N	?	Y	Y	N	?	Y	?
14	EE, HA	A2	E	C	med	?	R	Z-Wave	-	N	Y	N	N	N	N	N	N	N	N	online	Y	?
15[3]	EE, HA	A2	G	C[2]	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	online	Y	?
16	EE, HA	A2	G	C	low	-	R,W	WLAN, RF	N	N	N	N	N	N	N	N	N	N	N	online	Y	?
17	EE, HA	A2	G	C	low	-	R	WLAN	REST	N	Y	Y	N	N	N	N	N	N	N	online	Y	
18	EE, HA	A1	E	R&D	-	36	R,W	N	N	N	Y	Y	Y	N	N	Y	N	Y	Y	online	N	?

1: burglary prevention, security, others; 2: announced; 3: announced, very limited information

Table 9: *HEMS systems (continued)*

Product Nr.	***Aim***	***Product Class***	***Energy Type***	***Status***	***Investment Cost [€]***	***Running cost [€/a]***	***Wired/Radio***	***Standard Conformity***	***API***	***App Runtime Env.***	***DIY support***	***Online community***	***Blog***	***Gamification***	***Smart Grid interface***	***Metering Interface***	***Online software store***	***Developer support***	***Open Source***	***User Access***	***Smart Phone IF***	***Data security technologies***
19[1]	V, EE	A2	E	R&D	low	-	R,W	RF	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	both	Y	SSL/?
20[2]	V, EE	A2	G	C	0	-	-	-	-	-	N	Y	N	Y	N	Y[2]	N	N	N	online	Y	?
21	EE, HA	A1	G	C	low	-	R,W	WLAN, Z-Wave	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	online	Y	?
22[2]	EE	A2	G	C	?	?	?	?	N	N	N	Y	Y	Y	N	Y[2]	N	N	N	online	Y	?
23	EE, V	A2	E	C	low	-	R	N	N	N		N	Y	Y	N	N	N	N	N	online	Y	?
24	EE, HA	A2	E	C	med	-	R,W	Bluetooth	-	N	P	N	Y	N	N	Y	N	N	N	both	Y	?
25	EE, V	A2	E	Cty	low	-	R,W	N	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	both	N	?
26	EE	A3	E	C	low	-	R	N	N	N	N	Y	N	N	N	N	N	N	N	online	Y	?
27	EE, HA	A2	G	C	low	-	R,W	ZigBee	N	N	N	N	N	N	N	N	N	N	N	online	Y	?

1: Offering hardware components, aimed at electronic hobbyists. Only monitoring & visualization
2: Solely software based, metering connection through advertized utility involvement (only for participating utilities)

Table 10: *HEMS systems (continued)*

Product Nr.	Aim	Product Class	Energy Type	Status	Investment Cost [€]	Running cost [€/a]	Wired/Radio	Standard Conformity	API	App Runtime Env.	DIY support	Online community	Blog	Gamification	Smart Grid interface	Metering Interface	Online software store	Developer support	Open Source	User Access	Smart Phone IF	Data security technologies
28	M	A5	G	Comm	-	-	R,W	EnOcean, KNX, HomeMatic	Java/ OSGi	N	Y	N	Y	N	N	Y	N	?	Y	both	Y	?
29	M	A5	G	Comm	-	-	R,W	misc.	Y	N	Y	Y	N	N	N	Y	N	?	Y	offline	Y	?
30	M	A5	G	C/R&D	-	-	-	Z-Wave	N	N	N	N	N	N	N	N	?	N	N	online	?	?
31	[1]	A5	G	C	-	-	R,W	misc.	N	N	N	N	N	N	Y[2]	Y	?	N	N	both	Y	?
32	EE, HA	A5	G	C	-	-	R,W	?	N	N	N	Y	N	Y	N	Y	N	N	N	online	Y	?
33	EE, HA	A5	G	C	-	-	R	Z-Wave	Y	N	Y	Y	N	N	N	Y	N	N	Y[2]	online	Y	SOTA
34	[3]	A5	E	R&D	-	-	R,W	misc.	Y							Y						
35	EE, HA	A5	G	R&D	-	-	R,W	OGEMA 2.0	Y	Y	Y	N	N	N	Y	Y	N[4]	Y	Y	both	N	SOTA
36		A5	G	C	-	?	?	?	iOS	iOS	Y	-	-	-	-	N	-	Y	N	online	Y	?
37	EE, V	A5	E	C	low	60	R,W	Y	Y	N		N	Y	N	N	Y	N	Y	N	online	Y	?

1: proprietary middleware; 2: partly; 3: Monitoring & Control; 4: planned, but not yet established

3.2 Findings from the comparison

Regarding the investment cost, there is a wide range from less than 100 € up to more than 2000 €. A major cost driver is the professional installation which is strongly recommended for some systems. Most products do not charge running costs in terms of subscription fees or similar.

Many systems advertise with their do-it-yourself / plug-n-play capability and sophisticated MMI. Regarding the latter, products typically offer a web-based graphical interface and/or smart phone interface.

At the customer network level most systems rely on existing installations. At the sensor/actor most products would either offer own sensor/actor hardware or support off-the-shelf hardware. The sensor/actor network level is oftentimes covered by radio communication. Many systems support, but do not only rely on, wired communication. Z-Wave, ZigBee and WLAN are the in-home communication standards oftentimes supported.

However, there is much less support for complex devices, except in the case where the HEMS system and complex device manufacturer are the same. This situation will most likely only change with the emergence of standardized ICT interfaces for complex devices. Such interfaces are currently in preparation for specific device types (e.g. VHPready for heating devices).

With regards to the gateway level, we find a substantial number of A1 class systems which are distinguished by broad range of application and extensibility. However, much less systems feature an online store for software extensions, sophisticated developer support or an open-source licensing model.

Taking a look at gamification, we find first products implementing intrinsic user motivation, but nearly all of them are aimed at energy efficiency improvement. The products try to incentivize a more sustainable use of energy. Some of the products follow an extensive approach, addressing not only electricity and thermal energy, but also fields like transportation or rubbish avoidance. General home automation and home energy management products do not offer specific support for gamification yet, though.

Most systems are able to perform communication over the internet ("online"), meaning that data exchange to central servers is possible. This is usually relevant for the user interface, although some systems are also offering user interaction without internet connection. Even if state of the art data security measures are taken, there is currently no common, holistic standard. Considering data security and user privacy being one of the main HEMS barriers, this may be a critical point with regards to mass application.

4 SOFTWARE STANDARDIZATION AT THE GATEWAY LEVEL

4.1 Requirements

As seen from the comparison in above, many HEMS features depend on the gateway level software; e.g. data security, communication interfaces, extendability and manufacturer independence. Especially the latter two features call for an open runtime environment where software applications and hardware drivers from different developers can run and interact on. Such an environment must provide the applications with access to sensors/actors, data representation of connected devices and home appliances, MMI and smart grid interface. To enable manufacturer independence this access must be provided in such a form that an application developer does not need to know the actual hardware (including its communication interconnection) that will be used. This calls for abstraction using a standardized data model. Main requirements for designing such 'framework' are:

- Provide an environment for applications in the area of energy management and energy efficiency at the customers' sites in smart distribution grids
- Allow for access to devices and other hardware functionalities that are connected to the gateway hardware via standardized data models / device service models
- Allow for automated registration of new devices based on standardized data models and device services
- Access to data provided from outside the HEMS that might be relevant to various applications (such as the price of electricity) shall be available based on standardized data models
- Define standardized services of the framework for using these data models and device services
- Provide standardized services for functionalities that will be needed for many applications: The user web interface, persistent storage of certain types of data and logging

To make this possible an execution environment has to be specified as well as a framework providing services to access the components of the system as well as the devices and central information. As this requires standardization that should be supported by the players of the electrical energy supply as well as manufacturers from various fields, Fraunhofer IWES has started the Open Gateway Energy Management Alliance (OGEMA). The alliance has been developing such common specification and providing an open source reference implementation, soon available as version OGEMA 2.0 (www.ogema.org).

4.2 OGEMA 2.0

With regards to the generalized gateway software stack shown in Figure 3, OGEMA 2.0 is implementing the middleware level, comprising components as shown in Figure 5. As service delivery platform, OSGi is used and the JAVA runtime environment is put in as virtual machine.

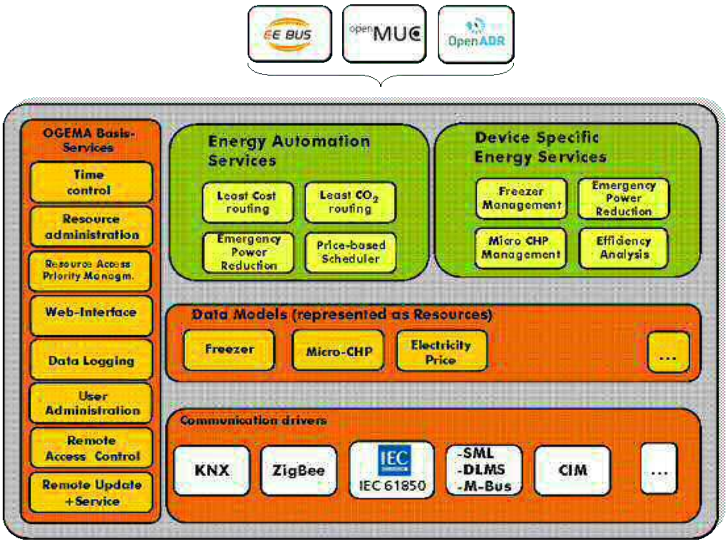

Figure 5: *OGEMA 2.0 system architecture.*

The OGEMA 2.0 reference implementation is currently demonstrated and further developed in the R&D project "OGEMA 2.0" by the three Fraunhofer Institutes IWES, IIS and ISE, comprising experiences from four major smart grid projects in the "E-Energy" framework in Germany. OGEMA 2.0 is also used in the ongoing national project INE-VES for implementing and demonstrating a HEMS for a residential hybrid generation system comprising photovoltaics, common heat and power generation and a stationary battery storage. Also, it is used in the European FP7 project EEPos for implementation of a neighbourhood energy management system [23] as well as project SEMIAH for development of a generic environment for the deployment and innovation of smart grid services in households [24].

An online store for OGEMA Apps is planned, but not yet established. Also, provision of smart phone interface and gamification is not part of the OGEMA 2.0 middleware, but needs to be provided by according applications, which are open to be designed by both commercial and non-commercial developers. Developer support is given by means of a public Wiki (https://www.ogema-source.net/wiki).

5 ACKNOWLEDGMENT

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STRUCTURED OPTIMIZATION FOR PARAMETER SELECTION OF FREQUENCY-WATT GRID SUPPORT FUNCTIONS FOR WIDE-AREA DAMPING

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ABSTRACT

Deployment of distributed renewable energy resources is increasing rapidly, which is leading to growing concerns over the impact of distributed power electronics energy converters on grid stability. In general, power electronic coupled systems do not provide frequency or voltage support through feedback compensation. This is leading to changes in utility interconnection requirements for distributed generation systems to provide voltage and frequency regulation ability through the use of newly developed advanced grid functions (AGFs). In this paper, the types of grid stability problems which can be mitigated by AGFs is expanded; in particular, it is demonstrated that the energy storage function which adjusts active power injection as a function of grid frequency, i.e., P(f) or freq-watt, can provide damping control using local frequency information. Specifically, a structured optimization scheme is presented that is scalable to multi-node distributed damping applications. An algorithm computes optimal damping controller gains for distributed resources that use only local frequency feedback. The local control may be implemented using the freq-watt AGF recently defined by the International Electrotechnical Commission (IEC). The proposed approach is applicable to local and inter-area oscillation damping and could be valuable for utility operations centers to identify appropriate gains for installed systems that implement AGFs.

1 INTRODUCTION

Inverters that implement advanced grid functions (AGF) have the ability to assist with bulk system frequency problems, distribution-level voltage deviations, and provide additional protection and resiliency to the electric power system. These capabilities come at limited expense but can greatly increase the allowed penetration of photovoltaic and other renewable energy on the grid, reduce the size of ancillary services, and provide wide-area damping control. This paper introduces advanced DER grid requirements, identifies problems where advanced grid functions mitigate grid performance issues and discusses the need for AGF parameter optimization. In particular, this paper presents a scheme for optimally selecting parameters for frequency-watt functions to provide wide-area damping.

Many advanced grid functions are required in Europe and, more recently, in certain jurisdictions in the United States. Advanced grid functions in photovoltaic and energy storage inverters have been mandated in national grid codes for low and medium voltage interconnections in Italy, Spain, Germany, Austria, France, and other European nations [1] - [2]. These functions include low and high voltage ride through (L/HVRT), active power as a function of grid frequency, reactive power injection/absorption, and remote disconnection requirements [3].

In the United States, many jurisdictions are considering modifications to the DER interconnection requirements to utilize renewable energy and energy storage systems to support grid frequency and voltage. California has modified the Electric Rule 21 tariff [4] to include several AGF implementations in order to help CA utilities meet their aggressive renewable energy targets [5] - [6]. In January 2013, the California Public Utilities Commission (CPUC) convened the Smart Inverter Working Group (SIWG) composed of state agencies, utility engineers, national laboratories, manufacturers, trade associations, and advocacy groups to provide consensus AGF recommendations to the CPUC [7]. Pulling from the AGFs defined in the International Electrotechnical Commission (IEC) Technical Report 61850-90-7 [8] (Table 1), the SIWG recommendations were split into three-phases of deployment [7]:

- Phase 1 - autonomous functions, e.g., volt-var and frequency ride-through
- Phase 2 - communication functionality
- Phase 3 - advanced functions requiring communications, e.g., real power curtailment

In December 2014, the CPUC commissioners unanimously ratified the first phase of the SIWG recommendations, and it is expected that CA Rule 21 will require the second two SIWG phases in the near future.

Similarly, in Hawaii, high penetrations of renewable energy resources are challenging grid operators. This has led the three Hawaiian Electric Companies to issue a joint request that all DER on Oahu, Hawaii Island, Maui, Molokai, and Lanai be reprogrammed with *wider* frequency and voltage ride-through settings [9]. The expanded ride-through settings are necessary so distributed generators do not trip when there are frequency or voltage excursions.

While certification and testing of advanced DER/inverter functionality is a major area of pre-standardization [10]-[12], selection of AGF parameters are also key to the successful deployment of the new technology. Just as the distributed controls of conventional generation must be harmonized to establish robust grid performance, the AGF parameters - e.g. curve shapes (deadbands and slopes), ramp rates, and delays - will become increasingly relevant as renewable penetration increases. In particular, unintended emergent behavior from untuned distributed controls can disrupt the grid as opposed to supporting it.

***Table 1:** IEC Technical Report 61850-90-7 Advanced Grid Functions*

IEC 61850-90-7 Command/Function		General Category
INV1	Connect/disconnect	Immediate control functions
INV2	Adjust max generation level	
INV3	Adjust power factor	
INV4	Request active power (from storage)	
INV5	Signal for charge/discharge action	
VV11	Volt-Var mode 11 (watt priority)	Volt-var management modes
VV12	Volt-Var mode 12 (var priority)	
VV13	Volt-Var mode 13 (static mode)	
VV14	Volt-Var mode 14 (no var support)	
FW21	Set active power limits based on grid frequency	Frequency-Watt management modes
FW22	Set active power input/output limits based on grid frequency	
TV31	Dynamic reactive current support	
L/HVRT	Connect/disconnect settings for Low/High Voltage Ride-through (VRT)	"must disconnect" and "must remain connected" regions for freq. and voltage
L/HFRT*	Connect/disconnect settings for Low/High Frequency Ride-through (FRT)	
WP41	Feed-in power adjust power factor	Watt-triggered behavior modes
WP42	Feed-in power adjust power factor	
VW51	Adjust power output to smooth voltage	Voltage-Watt management modes
VW52	Adjust power input/output to smooth voltage	
TMP	Temperature mode behavior	
PS	Signal mode behavior	
DS91	Modify DER settings	Parameter setting and reporting
DS92	Log alarms and events/retrieve logs	
DS93	Status reporting	
DS94	Time synchronization	

* Low/High Frequency Ride Through is not included in IEC TR 61850-90-7 but is being considered by some jurisdictions, like California [7].

The potential for disruption has been exemplified by the "50.2 Hz problem" in Europe, wherein a minor high frequency event would trip off gigawatts of distributed generation and lead to bulk system destabilization [13]. This will ultimately lead to expensive retrofits to more than 400,000 inverters to adjust the must-trip L/HFRT settings and add new frequency-watt functionality which gradually reduces output power of DER as the frequency increases above 50.2 Hz [14] according to VDE AR-N 4105 [15]. To further mitigate this issue, PV systems in Germany rated for less than 30 kW must limit their power to 70% of nameplate capacity or disconnect when the Distribution System Operator (DSO) sends the DER a signal; larger systems must have the remote DSO disconnection capability [16]. For this reason, detailed analyses of the desired and unintended grid effects must be performed prior to selection or standardization of AGF parameters.

At a more local level, the AGF parameters can significantly impact distribution system operations and controls. EPRI has investigated selecting PV advanced inverter settings for volt-var, volt-watt, and power factor to optimize voltage drop, flicker, feeder line losses, overvoltages, or reduce regulator tap operations [17]. From their study, the optimal parameters were difficult to determine and slight variations in the settings yielded significantly different responses on the feeder. The best settings depended on interconnection location on the feeder, feeder load level and topology, and if there were other systems with AGFs on the feeder.

While European grid codes strictly define the parameters for AGFs, in California, there are default settings with wide ranges of adjustability for AGFs [18]-[20]; thereby allowing utilities to adjust the settings as necessary for their jurisdiction, but transferring the burden onto them to select settings which have not been standardized across the industry. To advise utility regulators in these jurisdictions, high-fidelity, analytical studies and field experiments are necessary to determine proper advanced DER settings.

Many researchers have investigated different advanced grid settings for grid support behaviors. For example, voltage control on distribution circuits (volt/var, fixed power factor, etc.) to increase the hosting capacity and maintain the circuit within the required voltage limits were studied in [20]-[25]. Similarly, Winter *et al*. investigated volt-watt functions for increasing the hosting capacity in Europe [25]. While wind [26]-[27] and energy storage systems [28] are commonly studied for frequency control, and optimal frequency control settings have been determined to mitigate high frequency disturbances and provide frequency regulation [29]-[33], they have not been investigated to provide wide area damping.

Poorly damped inter-area oscillatory modes have been identified as contributing to the August 10, 1996 blackout and system break-up of the Western North American Power System (wNAPS) [34]-[36] and to the August 14, 2003 blackout in the eastern interconnection in North America [36]. Power transfers are often limited by stability constraints, leading to concerns over low-damping conditions. Such problems have also been cited in the Nordic power system [37].

Use of the wide area measurement system (WAMS) as feedback to implement wide-area damping control has been investigated. In [38], the authors implement a wide-area damping control scheme based on a 180 MVAr static VAr compensator (SVC) using WAMS feedback. In [39], [40] the authors investigate the use of energy storage to dampen inter-area oscillations using local and remote frequency feedback, such as that from a WAMS system. In [41], the authors study and advocate the use of power modulation of the Pacific DC Intertie (PDCI), a high voltage DC transmission line, to dampen North-South inter-area oscillatory modes. In [42], the coordinated modulation of the PDCI and energy storage is considered.

This paper expands on previous work to develop a damping control scheme based on distributed active power modulation to provide wide-area damping control. The control is implemented using a specific IEC TR 61850-90-7 energy storage function which adjusts active power injection as a function of local grid frequency, and the function parameters are selected using an offline optimization that considers the grid dynamics as a whole. This approach has a number of benefits:

a. In contrast to the methods in [38] -[42], AGFs do not rely on the wide area measurement systems (WAMS) or require network access to real-time phasor measurement unit (PMU) data.
b. Reliance on *large N* distributed resources provides redundancy and thus robustness.
c. Implementation of the required functions is already underway by manufacturers and can make use of existing hardware.

To compute the freq-watt parameters, the damping control problem is first represented as a distributed optimal control problem with a quadratic cost function that considers local frequency error, inter-area frequency difference, and the normalized control effort. The gains are computed so as to minimize the cost function. In particular, the cost function formulation is customized to select only available feedback terms, and a numerical algorithm based on the Anderson-Moore search [43] -[46] is performed to find the optimal gains.

The remainder of this report is organized as follows. Characteristics of oscillatory modes and damping control using real power modulation are reviewed in Section 2 with a focus on the Western North American Power System (wNAPS). In Section 3, the small signal model is presented, and the distributed optimal control problem is formulated. In Section 4, a method is presented wherein the optimal control problem is solved numerically using the Anderson-Moore descent function. Two examples are presented in Section 5 including an application of the control to a minniWECC model of the wNAPS. Finally, conclusions are provided in Section 6.

2 BACKGROUND ON POWER SYSTEM OSCILLATIONS AND DAMPING CONTROL

This section introduces electromechanical oscillations in power systems, with particular focus on the wNAPS. Recent investigations into the use of real power modulation to improve system damping are then summarized.

2.1 Characteristics of Oscillatory Modes

Electrical mechanical oscillations in power systems contain both *local* and *inter area* modes. An *area* comprises a large complex of electrically close generators. Local oscillation modes pertain to electromechanical oscillations of a single generator or plant against the rest of the system while inter area modes pertain to oscillations between groups of generators in one area against groups of generators in a different area [48]. Modes are characterized by frequency, damping and shape. In the Western North American Power System (wNAPS), several characteristic inter area modes have been known to recur and exhibit a low damping condition. These modes include the following [48]:

- North-South A mode, nominally near 0.25 Hz
- North-South B mode, nominally near 0.4 Hz
- East-West mode, nominally near 0.5 Hz
- British Columbia (BC) mode, nominally near 0.6 Hz
- Montana mode, nominally near 0.8 Hz

2.2 Understanding and Visualizing Mode Shape

Small-signal stability is defined as "the ability of the power system to maintain synchronism under small disturbances" [50]. Even under normal operation, power systems experience ambient perturbations primarily as a result of random fluctuations in load. A disturbance is considered "small" if the response of the system can be sufficiently described by a linearized model. The underlying assumption is that about a particular operating point the behavior of a power system can be described by a set of ordinary differential equations of the form,

$$\dot{x}(t) = Ax(t) + B_e u_e(t) \tag{1}$$

where $x \in \mathbf{R}^n$ is the system state vector, which includes small-signal rotor angle and speed deviations among other quantities and $u_e \in \mathbf{R}^m$ is an exogenous input that may represent probing signals or other inputs designed to excite a system response [48]. The eigensolution of the system matrix A in (1) yields all of the information required to describe the modal properties of the system.

The right eigenvector, called the "mode shape" vector, is a direct measure of the observability of a mode in the various states of the system. The magnitude and angle of the elements of the mode shape vector provide information about the relative oscillation amplitude and phase of a mode respectively. For analysis of inter-area modes, the elements of the mode shape vector corresponding to a common generator state, such as machine speed, are compared

Classically, mode shape data is presented in polar form [51]. Each element of the mode shape vector corresponding to a common system state is plotted as a phasor. The phasor tails are arranged at the origin, creating a compass-like appearance.

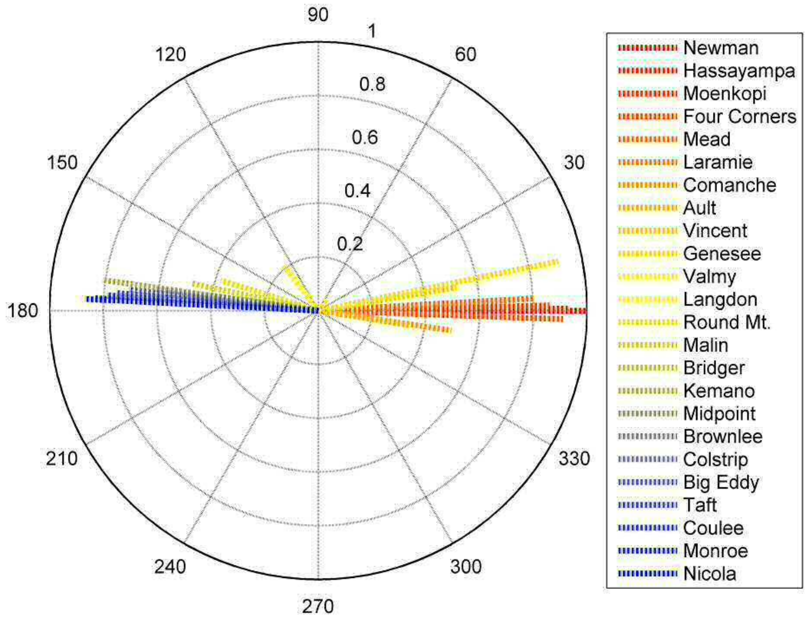


***Figure 1:** Compass plot example for mode shape data in Table 2.*

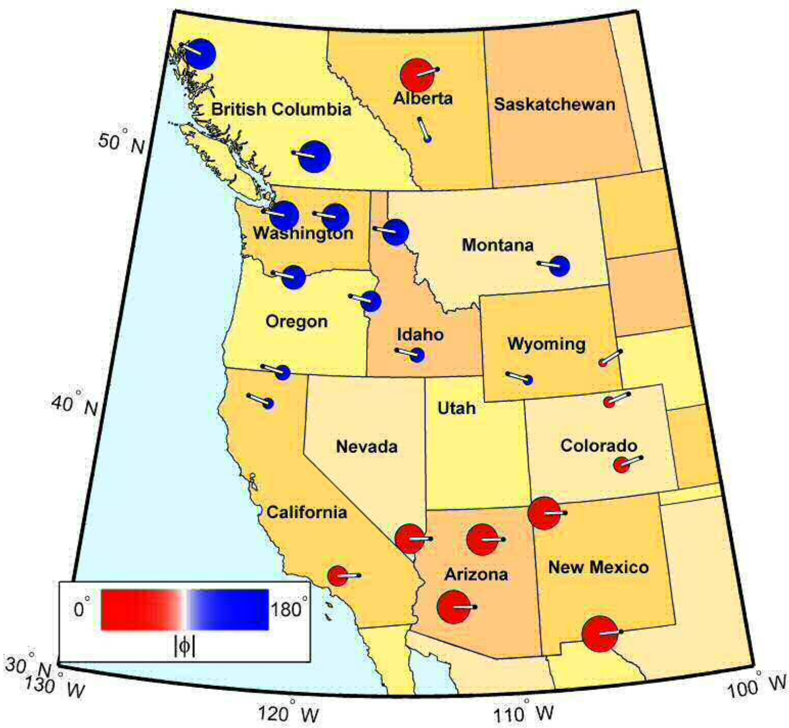


***Figure 2:** Representation of North-South B mode shape in the wNAPS.*

An alternative method of presenting mode shape data is to generate a map and place the tail of each phasor at the location where the state was measured. To facilitate numerical comparison, the oscillation amplitude is normalized by the largest value, and the bus with the largest amplitude is used as the angle reference. Figure 2 displays a mode shape map example. Therein, the red and blue markers represent key generators or plants that are oscillating against one another in the specified mode, and marker diameter indicates the amplitude of oscillation.

The mode shape data for Figure 2 is presented in Table 2 below. The columns are arranged in order of descending oscillation amplitude.

Table 2: *North-South B mode shape data for Figure 2.*

Bus	Amp.	Shape(*Deg.*)	Bus	Amp.	Shape(*Deg.*)
Newman	1.00	0.0	Nicola	0.87	177.1
Hassayampa	0.93	0.4	Monroe	0.83	176.8
Genesee	0.91	11.6	Kemano	0.81	171.9
Four Corners	0.91	−2.0	Coulee	0.79	175.8
Moenkopi	0.86	1.3	Taft	0.75	175.0
Mead	0.80	3.2	Big Eddy	0.71	173.7
Vincent	0.52	9.5	Brownlee	0.61	172.5
Comanche	0.50	−8.5	Colstrip	0.57	173.4
Ault	0.34	−9.1	Malin	0.48	167.9
Laramie	0.21	−6.8	Midpoint	0.43	172.1
Valmy	0.05	56.3	Round Mt.	0.38	162.8
			Bridger	0.29	171.6
			Langdon	0.21	127.5

3 OPTIMAL MULTI-NODE DISTRIBUTED DAMPING

In this section, the small-signal behavior of a power system is modeled as a linear system and modified to accommodate several distributed nodes participating in damping control. It is assumed that only local frequency measurements are available to each node.

3.1 Linearized Power System Model

To include the control action of distributed resources, the linearized power system model in (1) is expanded and represented as

$$\dot{x}(t) = Ax(t) + B_d u_d(t) + B_e u_e(t) \tag{2}$$

$$y(t) = Cx(t) \tag{3}$$

where $u_d \in \mathbf{R}^p$ is the input vector of real power injection intended to provide system damping and the output vector $y \in \mathbf{R}^h$ is a vector of generator speeds available for feedback.

As noted earlier, the stability of the system is described by the eigenvalues of the $n \times n$ matrix A, and the mode shape is encoded into the eigenvectors of A. Elements of the $n \times p$ matrix B_d would be determined by the location and interconnection of distributed damping control resources. The goal herein is to compute a $p \times h$ damping controller gain matrix K_d such that the eigenvalues of $A - B_d K_d C$ are further *left* in the complex plane, indicating improved damping. Furthermore, the selection of gain values should account for priorities concerning performance and control energy expended by the distributed resources. These priorities are represented using a performance index.

3.2 Definition of the Performance Index

The performance index, or *cost function*, is given as follows

$$J = \int_{t_0}^{\infty} \left(y^T Q y + u_d^T R u_d \right) d\tau \tag{4}$$

wherein the term $y^T Q y$ assigns a penalty for the state trajectory with $Q \succeq 0$, and $u_d^T R u_d$ penalizes the control energy with $R \succ 0$. For a damping control application $y^T Q y$ would be formulated to penalize frequency error (local and/or inter-area). The control design problem is thus to select the controller gain matrix K_d so as to minimize J.

The problem resembles the familiar *linear quadratic regulator* (LQR) problem wherein an optimal K_d is computed analytically through solution of the algebraic Riccati equation for full state feedback [49]. In this application however, since only the local system frequencies (and not the whole system state) may be used for feedback at each distributed asset, a conventional linear quadratic regulator (LQR) solution may not be used. Thus, the LQR solution is not used directly to compute K_d; rather the solution is attained numerically. Herein, the solution is attained using a method based on the Anderson-Moore search algorithm.

4 NUMERICAL SOLUTION OF OPTIMAL CONTROL PROBLEM

To compute the optimal gains, the cost function formulation is augmented to assign additional cost to the undesired or unavailable feedback terms, and an iterative numerical structured control algorithm (SCA) based on the Anderson-Moore search [45] - [46] is performed to find the optimal gains. The Anderson-Moore algorithm is an algebraic algorithm that is particularly effective at handling linear systems with saddle points [43] - [44].

4.1 Augmented Performance Index and Optimization Problem

The damping controller inputs are partitioned into p areas/subsystems wherein

$$B_d u_d = \sum_{i=1}^{p} B_{d,i} u_{d,i} \tag{5}$$

$$u_{d,i} = K_{d,i} C_i, x,\ i \in \{1,2,..., p\} \tag{6}$$

In addition, the R matrix is assumed to be diagonal $R=diag(R_1, R_2, ..., R_p)$, and the control inputs are normalized such that $\tilde{u}_{d,i} = \sqrt{R_i} u_{d,i}$ where $u_{d,i}$ is the i^{th} element of u_d. In this case the control inputs, u_d, are provided by the frequency-watt function for energy storage systems using a linear droop controller defined in Figure 3 by points (F_1, GP_1) and (F_2, GP_2). In some cases, it may be necessary to establish a deadband around the nominal frequency to avoid excessive cycling of the energy storage system, as shown by the dashed freq-watt function in Figure 3. Herein, focus is placed on implementing a configuration without a deadband. The gain values appearing in the K_d matrix would thus be equated with the negative of the slope of the line in Figure 3, $-\dfrac{GP_1 - GP_2}{F_1 - F_2}$.

An additional cost term is formulated to penalize the use of unavailable or undesired feedback signals, and the term is added to the cost function, resulting in the expression

$$\tilde{J} = \int_{t_0}^{\infty} \left(y^T Q y + \tilde{u}_d^T \tilde{u}_d \right) d\tau + \left\| \tilde{K}_{d,i} \Gamma_i C_i x \right\|^2 \tag{7}$$

where $\Gamma_i \succeq 0$ is a diagonal matrix of weights that penalizes feedback of select signals.

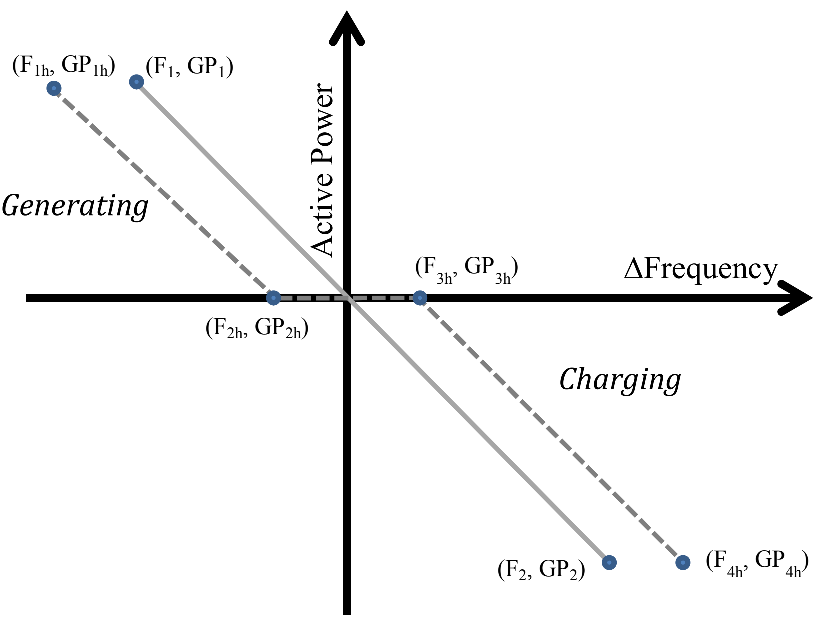


Figure 3: *The energy storage frequency-watt function with and without a deadband.*

The optimal damping control problem may be summarized as follows

$$\begin{aligned} &\underset{\widetilde{K}_d}{\text{minimize}} \quad \widetilde{J} \\ &\text{subject to:} \\ &(1)\ \dot{x}(t) = \left(A - B_d \widetilde{K}_d C\right)x(t) \\ &(2)\ Q \succeq 0 \\ &(3)\ \Gamma_i \succeq 0 \end{aligned}$$

The gain matrix K_d is then determined through proper scaling of $\widetilde{K}_d$.

4.2 Description of Anderson-Moore Search Algorithm

To solve the above optimization problem, a numerical algorithm is used to iteratively approach the solution.

The algorithm requires the calculation of some intermediate quantities. In each iteration, $\widetilde{K}_{d,i}$ values are updated and the system A-matrix is updated according to (8).

$$A_0 = A + \sum_{i=1}^{p} B_{d,i} \widetilde{K}_{d,i} C_i \tag{8}$$

Likewise, the Q matrix is extended to include the control signal penalties according to (9).

$$Q_0 = Q + \sum_{i=1}^{p} \left(C_i^T \widetilde{K}_{d,i}^T \widetilde{K}_{d,i} C_i + C_i^T \Gamma_i^T \widetilde{K}_{d,i}^T \widetilde{K}_{d,i} \Gamma_i C_i \right) \tag{9}$$

In each iteration, a descent direction for the gain matrix is computed according to (10),

$$\Delta\widetilde{K}_{d,i} = -\widetilde{K}_{d,i} - B_{d,i}^T P X C_i^T \left(C_i X C_i^T + \Gamma_i\, C_i X C_i^T \Gamma_i^T \right)^{-1} \tag{10}$$

where X is the state covariance matrix. Herein, the gain matrix update uses the descent direction with a step size parameter $\alpha \in (0,1]$ to adjust the rate of convergence. These algorithm steps are summarized in Algorithm 1 below.

In the next section, the algorithm is applied in the design of damping controllers for two example systems.

Algorithm 1: Structured Control Algorithm [45], [46]

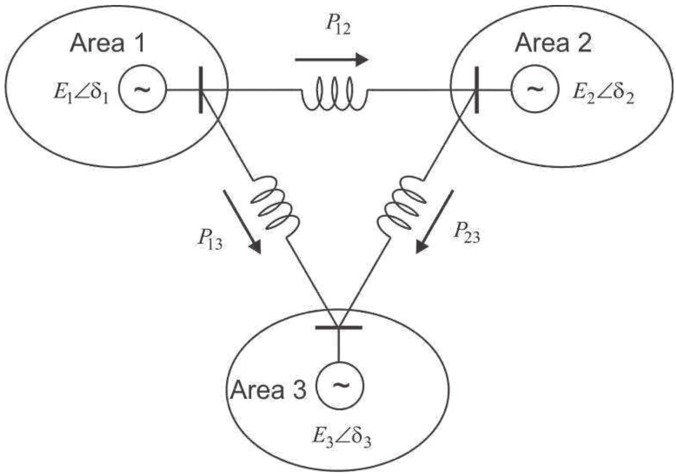
1:	Initialize the state Covariance X_0
2:	Initialize K_d, and segment into p rows: $u_{d,i}$, $i \in \{1,2,..., p\}$
3:	**while** change in gain is above tolerance $\Delta\|\tilde{K}_d\|_\infty > tol$, **do**
4:	Compute A_0 using (8)
5:	Solve $X_0 + XA_0^T + A_0X = 0$ for X
6:	Compute Q_0 using (9)
7:	Solve $Q_0 + PA_0 + A_0^T P = 0$ for P
8:	Compute new gain $\tilde{K}_{d,i} = \tilde{K}_{d,i} + \alpha\Delta\tilde{K}_{d,i}$ using (10)
9:	**end while**
10:	Compute $K_{d,i} = \dfrac{\tilde{K}_{d,i}}{\sqrt{R_i}}$, $\forall i \in \{1,2,..., p\}$

5 SIMULATION RESULTS

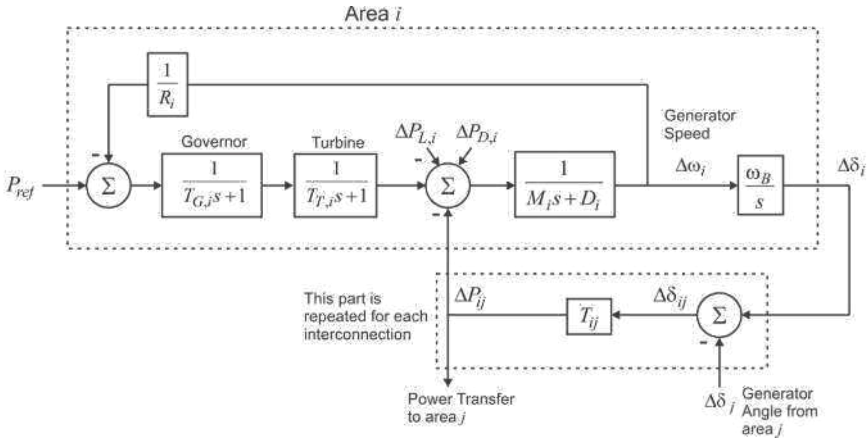
In this section, two control design examples are presented with simulation results. The first example considers a simplified three-area system with only primary speed control and demonstrates the ability of the algorithm to prioritize control objectives. The second example demonstrates the approach on a minniWECC model of the wNAPS.

5.1 Simplified Three - Area Power System

Consider a simplified three area system wherein each area is modeled as a single generating unit with droop, speed governor and turbine. Each area model is consistent with the non-reheat steam turbine model described in [50]. The system is illustrated in Figure 4.



a



b

Figure 4: *Three area system showing (a) overview diagram of power system and (b) a system diagram for an individual area.*

In each area, the generator speed is given as $\Delta\omega_i$, $i \in \{1,2,3\}$ (in per unit), the rotor angle is $\Delta\delta_i$ (radians), the inertia M_i (seconds) and damping coefficient D_i describe the rotor dynamics. The time constants associated with the speed governor and turbine are $T_{G,i}$ and $T_{T,i}$ respectively, and the droop coefficient is given by R_i. The synchronizing torque coefficients link an area *i* to an area *j*. The resulting system may be expressed using a state space model with $n = 12$: $x = \begin{bmatrix}\Delta x_1^T & \Delta x_2^T & \Delta x_3^T\end{bmatrix}^T$ where $\Delta x_i = \begin{bmatrix}\Delta\delta_i & \Delta\omega_i & \Delta Y_i & \Delta P_{m,i}\end{bmatrix}^T$ is the state vector for area *i*, with governor output ΔY_i and turbine mechanical power $\Delta P_{m,i}$. The base frequency of the system is given by ω_B. The damping powers are given by $u_d = \begin{bmatrix}\Delta P_{D,1} & \Delta P_{D,2} & \Delta P_{D,3}\end{bmatrix}^T$, and $u_e = \begin{bmatrix}\Delta P_{L,1} & \Delta P_{L,2} & \Delta P_{L,3}\end{bmatrix}^T$ are exogenous inputs representing changes in load-generation balance.

System parameters are given in Table 3, and the output matrix is given in (11), but the remaining state space matrices are not shown for the sake of brevity.

$$y = \begin{bmatrix}\Delta\omega_1 \\ \Delta\omega_2 \\ \Delta\omega_3\end{bmatrix} = Cx,\; C = \begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\end{bmatrix} \tag{11}$$

Table 3: *Parameters for Three-Area System*

Description	*Parameter*	*Value (units)*
Area inertias	M_1, M_2, M_3	6, 10, 5 (sec)
Area damping coefficients	D_1, D_2, D_3	0.4, 0.5, 0.3 (pu)
Governor Time Constant	T_{G1}, T_{G2}, T_{G3}	0.35, 0.30, 0.40 (sec)
Turbine Time Constant	T_{T1}, T_{T2}, T_{T3}	0.5, 0.60, 0.60 (sec)
Droop Coeff.	R_1, R_2, R_3	0.065, 0.05, 0.072 (pu)
Synchronizing Torque Coeff.	T_{12}, T_{13}, T_{23}	0.0104, 0.0087, 0.0066 (pu)
Base Generator Speed	ω_B	120π (rad/sec)

In this example, the objective focuses on mitigating a poorly damped inter-area mode at a frequency of 0.35 Hz; this mode is primarily realized as an oscillation between areas 1 and 3. The penalty matrix may be formulated to isolate this mode as follows

$$y^T Q y = \left(\kappa_1 \Delta\omega_1 + \kappa_2 \Delta\omega_2 + \kappa_3 \Delta\omega_3\right)^2 \tag{12}$$

where $\kappa_i \in \Re, i \in \{1,2,3\}$ are computed using terms in the right eigenvector.

The Γ_i matrices must be defined for each node location since only local feedback is used. These are defined as diagonal $h \times h$ matrices for the three areas as follows

$$\Gamma_1 = \eta \cdot diag([0 \quad 1 \quad 1]) \tag{13a}$$

$$\Gamma_2 = \eta \cdot diag([1 \quad 0 \quad 1]) \tag{13b}$$

$$\Gamma_3 = \eta \cdot diag([1 \quad 1 \quad 0]) \tag{13c}$$

where $\eta = 1000$ was found to work well in practice. Implementation of Algorithm 1 results in a gain matrix of

$$K_{d,local} = \begin{bmatrix} 1.5688 & 0 & 0 \\ 0 & 0.0896 & 0 \\ 0 & 0 & 1.6579 \end{bmatrix} \tag{14}$$

wherein the gain values used by the damping controller in areas 1, 2, and 3 appear in the first, second, and third rows respectively and are in per unit. For comparison, a "uniform gain" scenario is also considered wherein each area has the same local gain value of 1.5.

Finally, a scenario is considered wherein each node has access to frequency information of all three areas through a network (i.e. such as WAMS). Using the same expression for (12) but using $\Gamma_1 = \Gamma_2 = \Gamma_3 = 0$, the algorithm provides the following gains

$$K_{d,netw} = \begin{bmatrix} 1.2709 & -0.0943 & -1.1788 \\ -0.0925 & 0.0202 & 0.0533 \\ -1.1606 & 0.0369 & 1.2750 \end{bmatrix} \tag{15}$$

wherein some portion of the $u_{d,i}$ applied in each area is based on feedback of remote signals.

The effect of the control may be illustrated through examination of the root loci of $A - B_d K_d C$ for each case. In the four examples given: (1) without damping control, (2) control using uniform gain, (3) control using local frequency feedback $K_{d,local}$, and (4) control using networked feedback $K_{d,netw}$ the root loci are shown in Figure 5 with the targeted mode at 0.35 Hz circled.

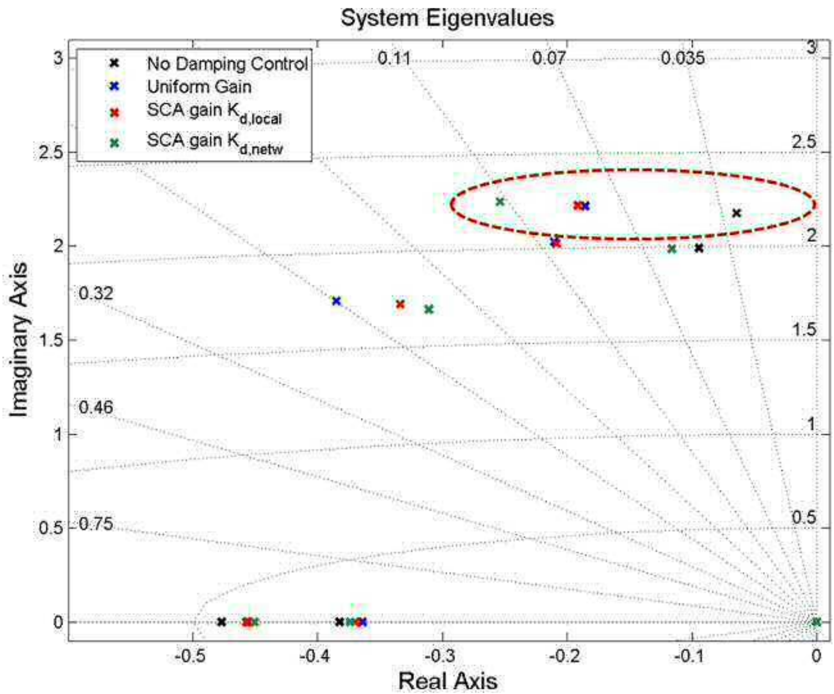


Figure 5: *Root Locus Comparison; 0.35 Hz mode is circled.*

Damping at the targeted mode is improved from 2.96% to 8.62% using the SCA computed gains using local feedback and similarly to 8.35% using uniform gains. It is noted the uniform gain was selected to give similar damping at this mode.

The SCA computed gains using network feedback achieve 11.28% damping at the targeted mode. All three control schemes add damping to the 0.315 Hz mode. The uniform case adds the most damping to this case, but this mode is not the priority as defined by the cost function. The optimal networked solution adds the least to the 0.315 Hz mode as the control energy is better applied to the mode of interest.

The distinction in performance is further illustrated through simulation of the system. The system was simulated for 60 seconds with a 0.02 per unit load impulse applied to area 2. A linear combination of frequencies $\kappa_1 f_1 + \kappa_2 f_2 + \kappa_3 f_3$ is shown in Figure 6 to illustrate the mode behavior of interest. It is noted that the uniform gain case and $K_{d,local}$ case perform similarly at this mode. The $K_{d,netw}$ case actually has a slightly greater oscillation than in the $K_{d,local}$ case, but the overall system cost is the smallest with the $K_{d,netw}$ gains, 7.08×10^{-7} as compared with 4.06×10^{-6} with the $K_{d,local}$ gains. This is due primarily to the disparity in control energy. The control inputs u_d are shown in Figure 7. For the uniform gain case, a disproportionately large level of control effort is seen in area 2. For the $K_{d,local}$ gains, the u_{d1} and u_{d3} control efforts are nearly equivalent to that seen in the uniform gain case; however, the u_{d2} control effort is greatly mitigated since this input has little controllability over the target mode. The network gain case with $K_{d,netw}$ shows a clear reduction in control energy over the other two cases; this is because the u_{d1} and u_{d3} controls are 180° out of phase, thus improving the inter-area damping torque with less control energy.

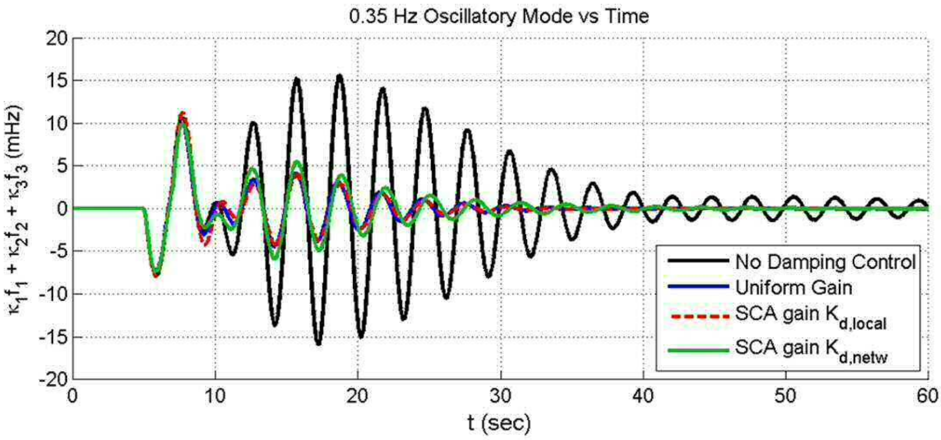


Figure 6: *Simulation of three-area system with impulse in area 1 showing oscillation of 0.35 Hz mode.*

Given this simulation result, the cost associated with the control effort $\int \left(u_d^T u_d\right) dt$ is 1.055×10^{-5} for the uniform gain case, but 3.74×10^{-6} for the SCA local feedback case; this is 64.5% less cost while accomplishing slightly better damping at the target mode. For the SCA gains with network feedback, the cost of the control effort is 3.47×10^{-7} which is a more than 90% reduction in cost while accomplishing a 30.9% improvement in the added damping over the same. The time domain response and thus the system cost will depend greatly on the disturbance input as well as the control gains. Not all scenarios will demonstrate such a large benefit for the proposed control. However, it is demonstrated that the algorithm can compute gains that result in a more optimal allocation of control energy. This would be useful for utilities that wish to realize prioritized wide area damping control given limited resources, i.e. PV curtailment or energy storage.

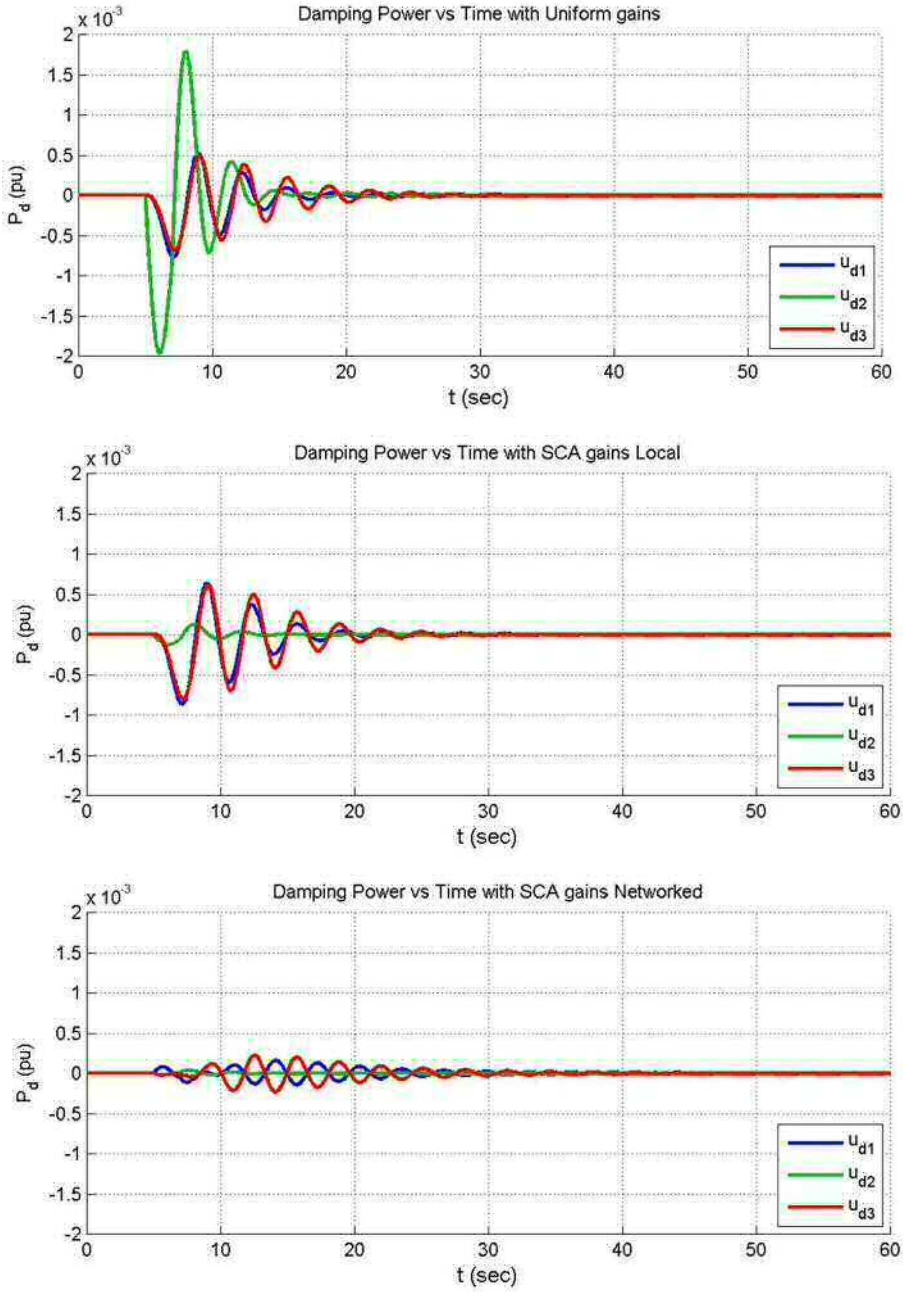


Figure 7: *Simulation of three-area system with impulse in area 1showing per unit damping powers with each meth.*

5.2 Damping Control Design in the wNAPS using the minniWECC

This section presents simulation results for a reduced order model of the Western North American Power System (wNAPS). The model, referred to as the minniWECC, was developed by Dan Trudnowksi and John Undrill [41] using the MATLAB Power System Toolbox (PST) simulation framework. The PST was originally developed by Prof. Joe Chow and Kwok Cheung in the early 1990's [52]. It was further marketed and developed by Graham Rogers, and is currently available from Luigi Vanfretti's web site [53]. The minniWECC contains 34 generators, 122 buses, 171 lines and transformers, 19 load buses, and two DC lines. Highly detailed generator models are used in the model. The minniWECC network is illustrated in Figure 8.

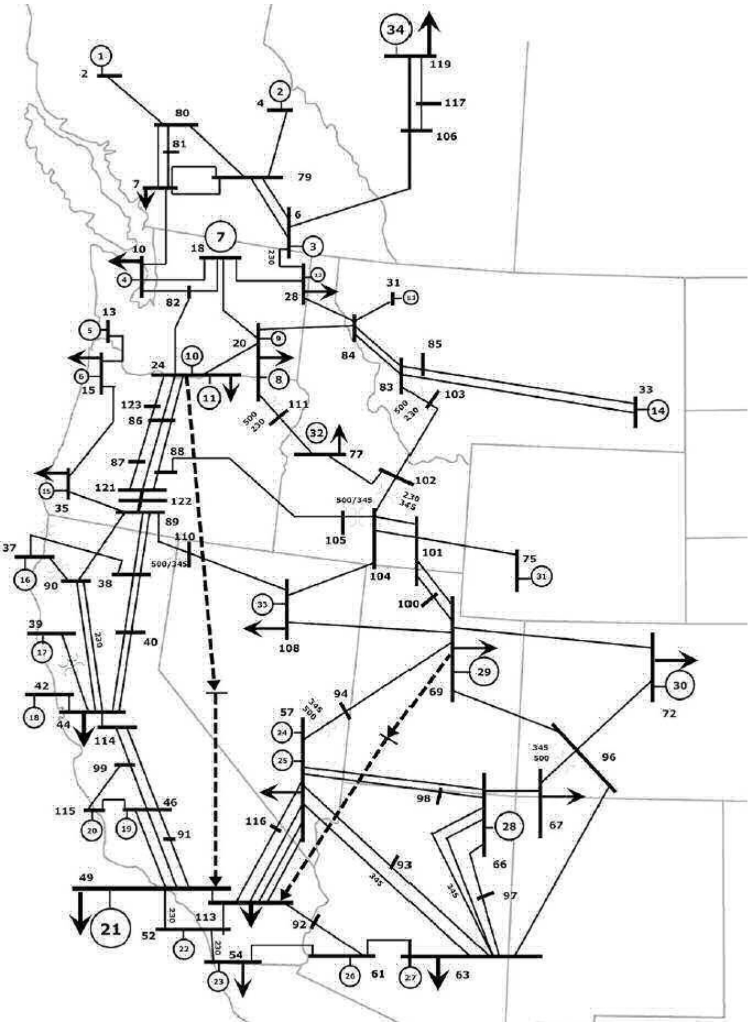


Figure 8: Illustration of minniWECC reduced order model, reproduced from [40].

For this analysis, a linearized model derived for the nonlinear minniWECC model was employed. The linearized model is obtained by perturbing the nonlinear system, using the **svm_mgen** routine in the Power Systems Toolbox. The result is state-space model with *A*, *B*, and *C* matrices that are used directly for defining (3) and (4) in the small-signal model.

Assuming a damping control resource may be installed at each of the *N* buses hosting a generator in the minniWECC model, a cost function is formulated to penalize East-West mode oscillations, and given as

$$y^T Q y = \left(\sum_{i=1}^{N} \kappa_i \Delta \omega_i \right)^2 \tag{16}$$

where the $\kappa_i, i \in \{1,2,...,N\}$ terms are determined similarly from the right eigen vector as noted in the three area example. Algorithm 1 was utilized to compute the optimal gains based on local frequency feedback. The results are shown in Figure 9. Therein, one notes the three largest damping gains are seen at generators 21 (southern California), 29, and 30 (Colorado).

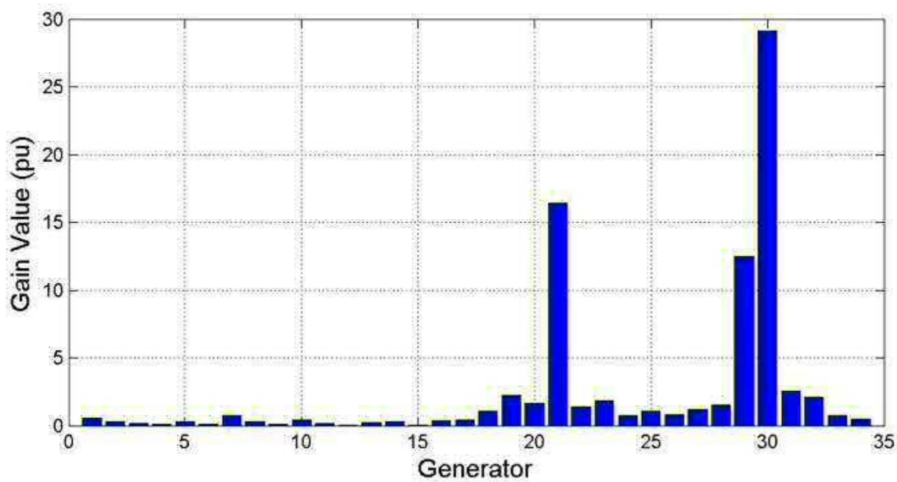


Figure 9: *Damping K gains determined by Algorithm 1 for the mini-WECC.*

The root locus is shown in Figure 10 wherein several electromechanical modes are illustrated. The cost function (16) was configured to penalize the East-West mode which is nominally at 0.50 Hz. Significant improvement is seen in several of the modes, including higher frequency (local) modes; however, most of the benefit is realized in the mode of interest, and no eigenvalues are seen to move to the right. Thus, the algorithm is successful in realizing the control objective.

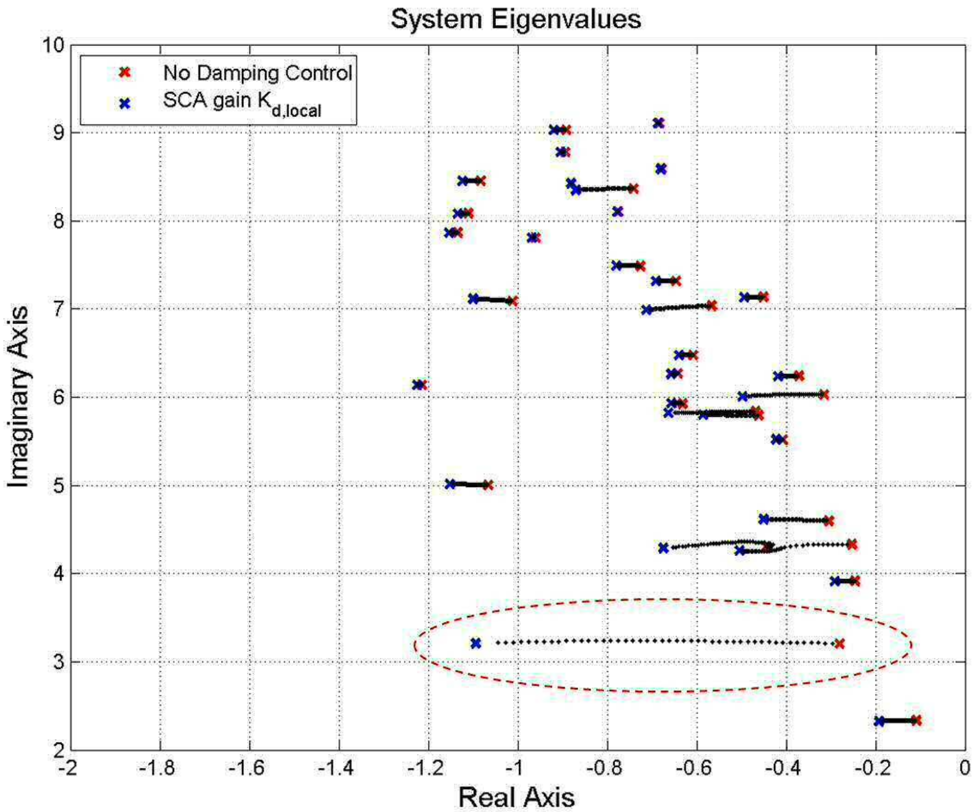


Figure 10: *Mini-WECC eigenvalues due to damping K gains; East-West mode is circled.*

6 CONCLUSIONS AND FUTURE WORK

Advanced grid function (AGF) requirements for renewable energy and energy storage systems are being added to many jurisdictions in Europe and the United States to provide grid operators additional control capabilities. These functions can be programmed to support grid frequency and voltage, and assist during grid disturbances. Many of the functions have been standardized in grid codes and IEC TR 61850-90-7, but the parameters for specific grid needs are still not well understood. While the optimal parameters are likely to change based on the grid topology and objectives, it may be possible to standardize methods for determining parameters which can achieve specific goals.

Studies that compare or optimize AGF settings cannot be comprehensive for all situations because of the wide range of distribution/transmission system variations, PV installation locations, and simulated PV penetration levels, so in many cases code and standards-making bodies rely on industry experts and anecdotal experience to select default AGF values. However, as the body of knowledge from simulations and field experience increases, better AGF parameters can be required by grid codes and programmed into DER.

This manuscript focused on the optimal allocation of control energy via selection of AGF parameters to assist transmission operators in preventing inter-area oscillations. Poorly damped oscillatory modes have caused multiple blackouts in the United States, but optimal distributed active power modulation can improve wide-area damping and prevent such events in the future.

Here, the frequency-watt function applied to energy storage systems (ESSs) was optimized using a numerical algorithm based on the Anderson-Moore search and a quadratic cost function that considered local frequency error, inter-area frequency difference, and the normalized control effort. In particular, the flexibility of the approach allows for specific oscillatory modes to be prioritized ensuring optimal use of the control energy.

Simulation of a three-area system and a model of the Western North American Power System (called minniWECC) demonstrated system damping was improved using the optimal local ESS control gains. The autonomous, local control alone is not as effective as using wide-area measurement system (WAMS) feedback, but this method has a distinct advantage in that it does not rely on WAMS network access to real-time PMU data. Therefore, this method is more resilient to communication failures by eliminating the need for external data, and it is more robust since it utilizes distributed redundant resources.

This work could be expanded in the future by providing wide-area oscillation damping using curtailed PV systems with generation headroom or reactive power (e.g., [54]). Therefore, future wide-area damping optimization should consider other DER types and advanced grid functions such as volt-var.

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STUDY OF OPTIMAL PLACEMENT OF ENERGY STORAGE UNITS WITHIN A DEREGULATED POWER SYSTEM

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ABSTRACT

This paper proposes an optimal placement of the energy storage units within a deregulated power system to with the aim of decreasing its hourly cost. Wind generation and loads are modeled using actual data approach. Based on a model of the electricity market, we minimize the hourly social cost using probabilistic optimal power flow (POPF) then use a Particle Swarm Optimization (PSO) compared with Genetic Algorithm (GA) to exploit wind power utility over a scheduling period. A market model is developed to evaluate the economics of the storage system based on the energy time-shift occasion from wind generation. The proposed method is used to carry out simulation studies for the IEEE 24-bus system. Transmission line constraints are addressed as a block for efficient wind power integration with higher diffusion levels. The distributed storage is then proposed as a solution to effectively utilize the transmission capacity and integrate the wind power more efficiently.

1 INTRODUCTION AND BACKGROUND

Power system transitions toward a deregulated structure, system operators must efficiently provide new services to accomplish electric market objectives. Energy storage can potentially add to social welfare while enhancing grid performance and reliability. These services allow managing peak demand, integrating alternating renewable energy technologies, providing auxiliary services such as load management, resolving transmission line congestion, deferring the transmission and distribution (T&D) upgrades, and supporting demand response resources [1].The renewable portfolio standards (RPS), which will increase renewables generation with alternating output, require appropriate strategies to maximize the utility of energy storage units [2]. Towards this end, the question of optimal storage sizing and placement must be addressed effectively [3].

Optimal allocation of storage in a deregulated power system with high wind penetration provides several benefits. These include market-based opportunity such as renewables energy time-shift, renewables capacity firming, and T&D upgrade delay in the form of revenue or reduced cost and storage-related communal benefits such as integration of more renewables, reduced emissions, and improved utilization of grid assets [4]. A cost-benefit analysis is also required for an economic evolution of the storage systems. Limited transmission capacity during high wind periods may necessitate wind power based energy supply restriction which, depending on contractual agreements, may result in a loss of revenue to the wind generators or an added cost to the grid operators. Storage of the wind energy in excess of transmission capacity makes it available for later dispatch when transmission capacity is available. Thus, optimal allocation of energy storage results in efficient utilization of transmission capacity. The irregular nature of wind resources imposes a significant level of indecision about the final output power with a typical error in the range of 30% - 50% [5]. Optimal placement of sufficient energy storage capacity provides the required flexibility to fulfill the wind power supply schedules cleared in the market and decrease against forecast uncertainty [6], [7]. This flexibility can be reached by storing the excess energy when the wind production is higher than the cleared schedule. The stored energy is then used to avoid the consequences associated with producing less energy than the cleared schedule. Moreover, optimal placement of storage systems is required to utilize the storage capacity more efficiently while maintaining the transmission thermal constraints. Subsequently, the net power delivery follows the schedules cleared in the market more accurately. The energy storage units and their applications in a deregulated market environment were investigated in [8]. All these studies assumed that the dispatching the storage devices does not affect market prices.

This manuscript proposes a market-based probabilistic optimal power flow (POPF) at the level of power system integrating wind generation and storage units. The proposed methodology considers storage units as market participants in the market-clearing process, optimally places and schedules them in order to minimize cost using PSO optimization and two-point estimation. It also presents probabilistic models of wind generators and loads based on actual data. The storage system is modeled either as a variable load or as a variable generator. Energy storage serves as a variable load to store the wind power based excess energy during the off-peak hours when the wind power exceeds the load. It then serves as a variable generator during the peak hours of the day to optimize wind power based revenues. Storage distribution is also proposed as a solution to increase wind power utilization and mark opportunities for higher wind penetration levels.

2 METHODOLOGY

The uncertainties of wind generation and load are characterized using probability density functions and Wind speed statistical model is given by [9]-[10],

$$f_v(v) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} \tag{1}$$

where,

k = Shape factor for Weibull distribution

λ = Scale factor for Weibull distribution

The output power of a wind generator is a function of wind speed and given using curve fitting, maximum likelihood guesses of the Weibull distribution parameters are calculated for historical hourly wind speed data by [11]. A gaussian distribution is used in this paper to statically model the load variation. The probability density function (pdf) for a Gaussian distribution is using curve fitting; maximum likelihood estimates of the gaussian distribution parameters are calculated for historical hourly load data.

3 NOMENCLATURE

a_i, b_i	Bid function coefficients of the ith generating unit
A	Equivalent annual cost of the investment in $
C_c, C_P, C_S	Cost of compressor, power, and energy for Compressed Air Energy Storage (CAES)
C_{Inv}	Total investment cost for CAES in $ / kWh
C_{NG}	Natural gas cost for CAES in $ / kWh
C_{OM}	Fixed operation and maintenance cost for CAES in $ / kWh
C_{OP}	Operational cost for CAES in $ / kWh
D	Discount rate
d_{hs}	Hourly discharge of the system
G_W, G_{Wr}, G_{Wt}	Output power of wind, rated wind power and wind power at time,t

L_t	Load demand at time t
N_g	Number of generating units in MW
P_d	Power demand
P_t	Power of the storage system
V	Wind speed at m/s
η_S	Efficiency of the storage system
λ	Scale factor
$P_{gi,t}$	Generation of i[th] generating unit at time,t
μ_i^{max}	Lagrange Multiplier of upper i[th] generation

3.1 Modeling of Storage System

This paper uses an energy storage system to time-shift electric energy from renewable generation. The energy storage unit is charged using wind power in additional of the load or transmission capacity that would otherwise be reduced. This occurs when (off-peak hours) or transmission capacity limits restrain the transferred wind power. The stored energy is discharged during peak load hours of the day when it is most valuable [12].

a) The considered equation used for charging of the storage unit

$$S_t = (1 - d_s)S_t - 1 + \eta_s(G_{Wt} - L_t) \quad (2)$$

Where,

$$S_t = Energy\ stored\ in\ the\ storage\ system\ at\ time, t$$

b) The considered equation used for discharging the storage unit

$$S_t = (1 - d_s)S_t - 1 + (G_{Wt} - L_t) \quad (3)$$

The constraints of the reservoir are

(i) Storage capacity

$$S_{min} \leq S_t \leq S_{max} \quad (4)$$

(ii) Power storage system

$$|P_t| \leq P_{max} \quad (5)$$

3.2 Market-Based Optimal Power Flow

The objective function is formulated using OPF each market participant submits an hourly price bid in the form of marginal cost. The bids are taken as inputs to the OPF which optimally determines the supplies and locational marginal prices (LMPs) to minimize the hourly social cost (HSC). A bilateral contract between the wind supplier and storage owner is used to purchase the curtailed wind power. The HSC can be formulated as a function of generation bids. Using incremental costs for bidding, the objective function of electricity market-based OPF is as follows [13], [14]:

Objective function = Min $\{\sum_{i=1}^{Ng} P_{gi,t}(a_i P_{gi,t} + b_i)\}$

$$=\text{Min } (HSC_t) \quad (6)$$

HSC is in the form of the generation cost. The independent system operator (ISO) performs this market-clearing process while satisfying the following equality and inequality constraints.

The Lagrange function of the market based OPF is

$$LF_T = HSC_T + \lambda_{i,t}\left(\sum_{i=1}^{n} P_{di,t} - P_{gi,t}\right) + \sum_{i=1}^{Ng} \mu_i^{max}\left(P_{gi,t} - P_{gi-max}\right) + \sum_{i=1}^{Ng} \mu_i^{min}\left(P_{gi-mim} - P_{gi,t}\right) \quad (7)$$

Using, first order derivative, Lagrangian function w.r.t.$P_{gi,t}$Will produce the

Locational Margin Price (LMP) at each bus

$$LMP_{i,t} = \lambda_{i,t} = \frac{\partial HSC_t}{\partial P_{gi,t}} + \sum_{i=1}^{Ng} \mu_i^{max} - \sum_{i=1}^{Ng} \mu_i^{min} \quad (8)$$

In the LMP market, loads pay and generators are paid based on the LMP. The

income of a generator at bus and hour is

$$Inc_{gi,t} = LMP_{i,t} \times P_{gi,t} \quad (9)$$

3.3 Market-Based Probabilistic OPF

Uncertainty factors such as wind power output and variable loads can be considered in power flow computations by using POPF [15]. Several methods have been proposed to perform the probabilistic analysis in POPF problems. These methods are classified as simulation, analytical, and approximate methods. Monte Carlo simulation (MCS) is a simple and accurate method that uses the historical data of probabilistic quantities to find their pdfs. The random values from these pdfs are selected and used to quantify the uncertainties. The large computational effort is the main obstacle for the efficient use of this method [16].

The main disadvantage of analytical methods for POPF is their complicated mathematical computations [17]. Several approximate methods have been proposed to reduce the computational burden and mathematical calculations associated with MCS and analytical methods, respectively. Point Estimation (PE) is a popular approximate method because of its accuracy, simplicity, and speed [18]. Two point estimation (2PE) [19], a variation of PE, is applied in this paper to model uncertainties the application of this method for POPF problems demonstrates a high accuracy level when compared to MCS while significantly reducing the computational burden [20],vectors of input and output random variables and the corresponding nonlinear function.

$$\text{X} = [Wind\ Speed, Loads] \quad (10)$$

$$\text{Y} = [HSC] \quad (11)$$

$$Y = H(X) \tag{12}$$

Where, H is a function governing the probabilistic market-based OPF with energy storage integration and wind generation. Two concentrations are used to replace by matching its first three moments. The functional relation between k^{th} random variable and is then used to generate two estimates of variants .and scale the estimates to compute the expected value and standard deviation of the output. The proposed method uses Optimum Power Flow (OPF) based on unit recommitment to dispatch the generation for each hour. The unit recommitment procedure provides a mechanism to shut down generators that are expensive to operate and finds the least costly commitment and dispatch. This results into an economic operation of the system over the scheduling period [21]. The proposed method incorporates energy storage into the market-based OPF model to time-shift electric energy from the wind power. Towards this end, energy storage is considered either as a variable load or as a variable generator. When the wind power is higher than the load (off-peak hours) or exceeds the transmission capacity limits, energy storage serves as a variable load to store the excess wind energy that would otherwise be curtailed. The proposed POPF algorithm for the scheduling period is outlined as follows:

1. Load the input data (wind speed and load)
2. Set t = 1
3. Assign appropriate pdf to each probabilistic variable.
4. Set $E(Y) = E(Y^2) = 0$
5. Set k = 1
6. Determine the necessary parameters for the 2PEM
7. Set the concentrations using the input vector using output of wind power.
8. Calculate Z
9. If $G_W - L > 0$ calculate the load constraint
10. Run the deterministic market-based OPF incorporating the storage system as either the variable load.
11. Calculate the state of charge using (2), (3).
12. Calculate the HSC.
13. Update the mean and mean square
14. Set and repeat steps 6-13 for all input variables.
15. Calculate the expected value and standard deviation
16. Set and repeat steps 3-15 until.

The above POPF algorithm minimizes the system social cost while satisfying the constraints for each hour over the scheduling period. Thus, it maximizes social welfare [22].

3.4 PSO Optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird blocking or fish schooling. A population is initialized of random feasible solutions and searches for optima by updating generations. In PSO, the potential solutions, called particles have their own positions and velocities move in the search space of an optimization problem by following the current optimum particles. Each particle tracks its own best position found so far in the exploration and each particle searches for better positions in the search space by updating its velocity. The movement of each particle naturally evolves to an optimal or near-optimal solution.

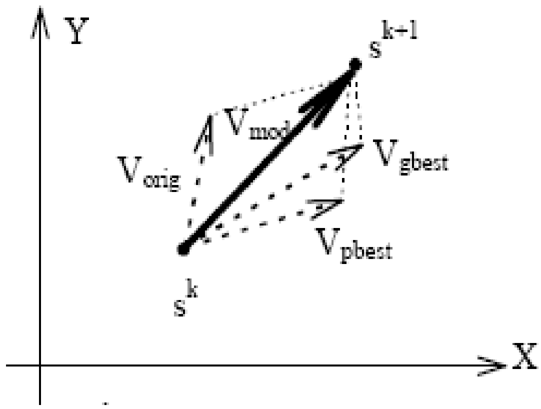

Figure 1: *Behavior of particles in PSO.*

The position of each agent is represented by XY-axis position and the velocity (displacement vector) is expressed by Vx (the velocity along X-axis) and Vy (the velocity along Y-axis). The Identification of the agent position is realized by using the position and the velocity formation. The behavior of particles in PSO is shown in 1.Each agent or particle knows its best value so far (p_{best}) and its x, y position. Each agent knows the best value so far in the group (g_{best}) among p_{bests}. Each particle tries to modify their position using the following information:

- the current positions (x, y),
- the current velocities (Vx, Vy),
- the distance between the current position and the p_{best}
- the distance between the current position and the g_{best}

The basic equation for the optimization of nonlinear functions using particle swarm optimization technique

$$V_i^{gen} = w.V_i^{gen-1} + C_1 \text{ rand } (P_{besti} - S_i^{gen-1}) + C_2 \text{ rand } (g_{besti} - S_i^{gen-1}) \quad (13)$$

$$S_i^{gen} = S_i^{gen-1} + V_i^{gen},$$

Where w is updated at each iteration:

$$w = w_{max} - \frac{w_{max} - w_{min}}{gen_{max}} \text{ gen.}$$

here, $w_{max} = 0.9$; $w_{min} = 0.4$; *and* $gen_{max} = 500$ *and* Gen = current iteration; C_1 and C_2 are set to 2.0[24].

using Particle Swarm Optimization algorithm (PSO) provides a powerful tool to obtain the optimal placement of the storage in a deregulated power system with high wind diffusion. Generally, a set of initial populations arbitrarily chosen from the feasible solution space is used to start the PSO. The fitness function is evaluated for each solution, and the solutions are consequently ranked. The population then evolves through several operations such as reproduction, crossover, and mutation to optimize the fitness function and obtain the final optimal solution. The process is repeated until the implementation criterion is satisfied. This evolutionary algorithm is preferred over classical optimization approaches because it can handle the nonlinear, non-convex, and mixed-integer optimization problem of the storage placement.

The non-convexity of the problem makes it difficult for classical optimization methods to obtain a global optimum. PSOs, on the other hand, globally search the domain of possible solutions for an optimal solution on [23]-[24].PSO also requires less number of variables than classical optimization approaches. However, if not carefully implemented, PSO can converge to a local minimum. Several implementation strategies can be applied in order to avoid convergence to local minima. A large population size increases the probability of convergence to the global minimum, but this significantly increases the computation burden. Two elitism children are maintained for each generation to ensure retaining desirable solutions. A good balance between crossover and mutation offspring is achieved by maintaining the crossover fraction around 78%, to satisfy the constraints, a large penalty factor is assigned to solutions that violate a constraint.

This paper uses PSO-enhanced electricity market-based POPF to determine the optimal locations of storage units within a deregulated power system with wind generation. The solution minimizes the hourly social cost of the system and maximizes wind power utilization in a power-pool market over the scheduling period. The CAES must have sufficient storage capacity to store the wind energy in excess of the load while satisfying transmission constraints. The storage capacity is then calculated based on the optimization results. The fitness function of the proposed optimization method the following

$$\text{Fit. Function} = \text{Max}\ \{Wind\ Utilization\}$$
$$= \text{Max}\left\{\frac{\sum_{t=1}^{t}\sum_{i=1}^{n} P_{di,t} - \sum_{t=,i=1}^{T}\sum_{i\ in\ \ gen,storage}^{Ng} P_{gi,t}}{\sum_{t=1}^{T} G_{wt}}\right\} \tag{14}$$

Fig. 2 shows the flowchart for the proposed method. The first population of the decision variables is initialized to optimally locate the storage systems and maximize the wind utilization

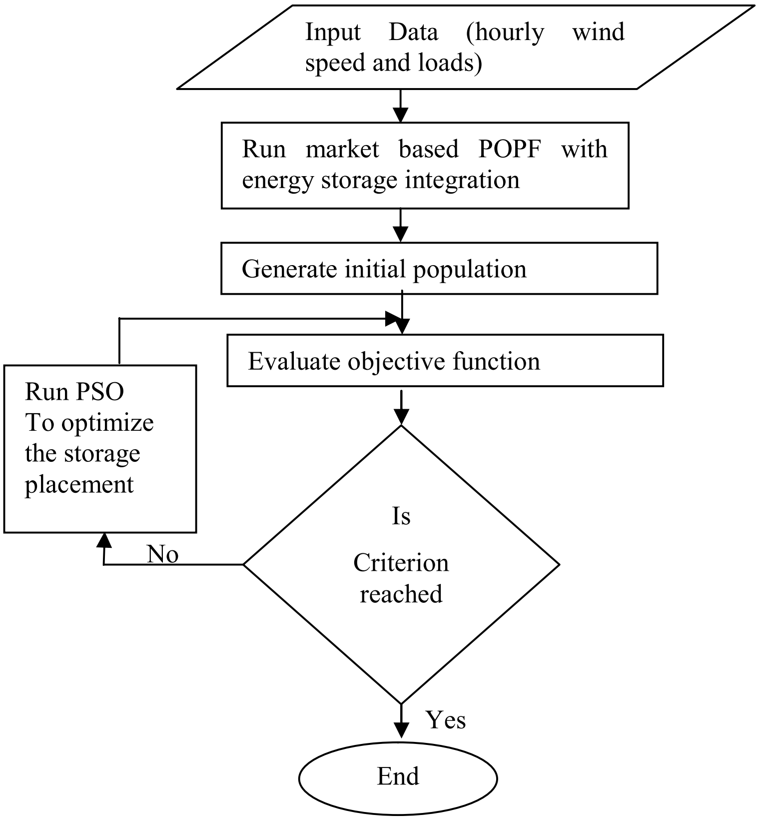

Figure 2: *Flow chart for the PSO based Enhanced POPF.*

4 RESULTS AND DISCUSSION

The proposed POPF optimally place energy storage within the power system integrating two different wind penetration levels. The cost is the sum of the equivalent investment cost and operating cost for 24 hour scheduling period. The primary energy source of the wind form installed at bus 14 has variable load of 498.5 MW to 754.09 MW-initially, all generating units are committed for each hour of scheduled period. First market based POPF with no storage is used to calculate wind utilization for 24 -hour scheduling period, then storage units are placing using PSO enhanced market based POPF to maximize wind power utilization, Figure.2 shows the flow chart for the proposed method. Population, decision variables and fitness functions are calculated using [11]. Simulation results are studied in IEEE 24 bus test system having 11 generator buses and 17 load buses. Figure 3, 4 and 5 shows the state of storage unit, wind generation and load demand for 24 hour duration. Figure 6 shows the location of the marginal price at wind penetration level at 45%, table 1 show the optimal placement of energy storage systems.

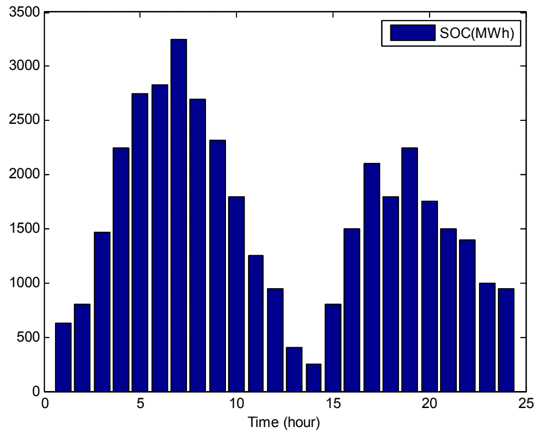

Figure 3: *State of storage unit (in MWh) for 24 hours.*

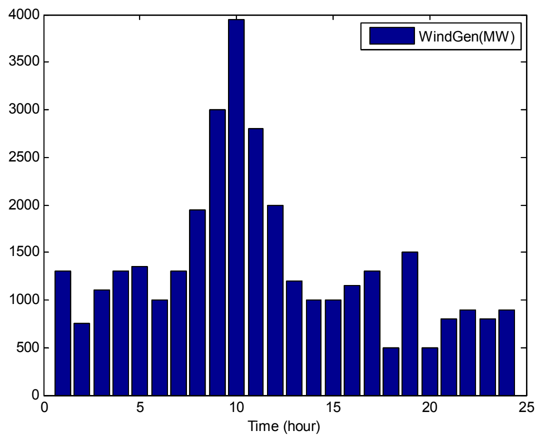

Figure 4: *Wind Generation (in MW) for 24 hours.*

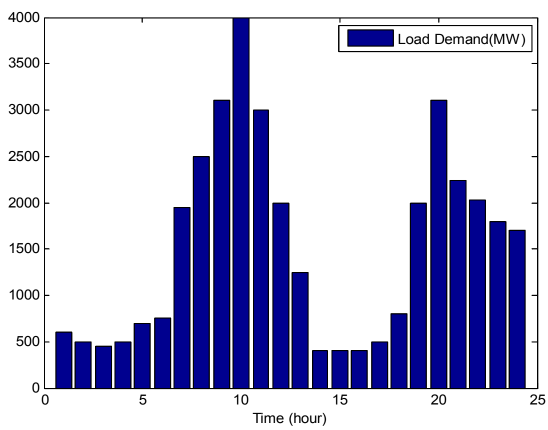

Figure 5: *Load Demand (in MW) for 24 hours.*

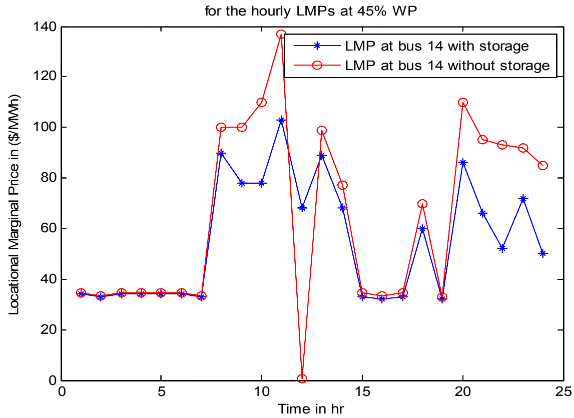

Figure 6: *Location of marginal price.*

From [11], the wind penetration level considered for 45% optimal placement of energy storage system, wind utilization is considerably increased using PSO based POPF compared with GA.

Table 1: *Optimal placement of energy storage system for 45% WP using POPF*

WP Level		***Optimal placement bus***	***Energy rating Mwh***	***Power rating MW***	***Arbitrage Revenue (10^3\$)***	***Cost (10^3\$)***	***Wind Utilization (%) GA***	***PSO***
45	No storage	-	-	-	-	--	72.4	73.2
	storage	14	323	754	317	255	92.6	93.8

5 CONCLUSION

The proposed paper has investigated the optimal placement of energy storage within a deregulated power system to minimize the hourly communal cost. Using historical data curve fitting, both wind and load were stochastically modeled. A Power System Optimization algorithm based POPF with energy storage and wind generation maximizes the wind power utilization for the scheduled period of 24 hours. Simulation result for IEEE 24 system demonstrates the advantage of the wind storage for efficient integration with penetration level. Optimal placement of energy storage system for 45% WP using PSO based POPF considerably increased the wind utilization.

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GERMAN GRID CODE ASPECTS DISCUSSION: LOW VOLTAGE RIDE-THROUGH OF CONVERTER BASED DECENTRALIZED GENERATION

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Keywords: Low voltage ride-through; decentralized generation, grid codes, renewable energy; active distribution networks.

ABSTRACT

As the Decentralized Generation (DG) penetration dramatically increases in distribution networks, Low Voltage Ride-Through (LVRT) capability of DG becomes a critical issue that has to be investigated and developed. This paper reviews the LVRT requirements of DGs in German grid codes. As the national grid codes are basically valid for transmission networks where the X/R ratio is high; it will be unsuitable to be implemented in case of active distribution network. In the current study the inverter based DG mathematical model was developed and the impact of the active and reactive powers injected at the point of common connection (PCC) in case of fault was analysed. The main objective of the study was developing the German grid code in order to enhance the LVRT capability of the converter based DG units. The effect of X/R ratio on the LVRT capability was investigated. The developed approach fully utilizes the DG's capability of voltage support and takes the safety of equipment into account as well. The results of the proposed approach were compared with that of the German code and show a good agreement.

1 INTRODUCTION

One of the prerequisites for stable power system operation is the balance between the load and generation. Large scale storage of electrical power does not exist till now; therefore all demand power has to be generated almost at the same moment. Control schemes are designed on power plants to guarantee security of supply, to a certain extent, continuously restore the balance or otherwise load is switched off gradually. The unbalance created by the loss of a power plant needs to be covered by other power plants connected to the power system. Due to the increase of the Decentralized Generation (DG) power in the low voltage and medium voltage networks, the generated power by these units becomes more and more important in the total power generation [1, 2].

Integration of DG not only alters the power flow but will also change the fault currents in the distribution grid, which can affect proper operation of the current protective system, which may result in false tripping, blinding of protection and reverse fault currents [3]. Therefore, DG disconnection is performed in order to facilitate restoration of the electricity supply in the event of operating disturbances, to avoid infeed continuing during a fault in the grid and to avoid plant and equipment being exposed to abnormal operating conditions [4]. Up to a few years back standard practice, taken by grid operators, require immediate disconnection of the DGs in case of fault or short circuit. Immediate disconnection of DG unit can restore the distribution network to a network which has only one source of supply and therefore, the protective system will function as it was implemented to do so during the design state of the network [3, 5]. There are more benefits that DGs can help in term of power system stability. If Power Electronic Converter (PEC) based DGs is disconnected from the grid during fault, then maximum rotor acceleration is restricted and thus transient stability is improved. On the other side with large penetration level of DGs, that will result in an imbalance between loads and generation which may lead to poor frequency and voltage stability problems [3, 6]. However keeping the DG connected during fault can help damping out the oscillations faster because the immediate reaction of the PEC isn't bounded by its inertia. That means it can supply reactive power during the fault and contribute to the fault current [3, 6]. Different grid codes require from the large DG units which are connected to the transmission networks such as wind farms to stay connected in the case of emergency in order to share actively in the voltage control based on specific criteria [7].

The Fault Ride-Through (FRT) capability of generators, also known as low-voltage-ride-through (LVRT) capability, is identified as "*the ability of generators to remain stable and connected to the network when faults occur on the transmission network*" [7, 8]. The main objective of the FRT-requirements is to prevent disconnection of an undesirable portion of power generation during contingencies.

In the current study LVRT-requirements in different national grid codes are discussed. Based on the German grid codes the X/R ratio of the grid impact was analysed. The inverter based DG mathematical model was established and the impact of the reactive power supplied at the point of common connection (PCC) was analysed. A new voltage support control strategy to enhance the LVRT capability is proposed. The proposed method takes the safety of the equipment into account. The results of the proposed method are finally compared with the German grid code results on a simple test system. The simulations were conducted using the PowerFactory DIgSILENT software.

2 REQUIREMNTS FOR LVRT CAPABILITY IN NATIONAL GRID CODES

Low voltage ride-through requirements are advanced grid-connection requirements which are technically justified in countries where DG units are connected with high capacities and supply a high percentage of the total demand. In fact, if the DG penetration level is low, then there is no need to require DG to remain connected and support the grid during the fault [3, 8, 9]. The evaluation of the need for such requirements should be conducted by government bodies or TSOs which are fully separated from any generation activities, therefore biased decisions can be avoided [8]. Some national grid codes (e.g. Denmark and Ireland) have different fault ride-through requirements for distribution and transmission networks, whereas other national grid codes focused only on the transmission level (e.g. Germany and Spain). In the following, LVRT requirements for DGs installed in Germany, Ireland and Spain are briefly discussed.

2.1 German grid code

The protection system is responsible to isolate the faulted area only. The generating unit shall fed short-circuit current into the grid during the fault period if the fault is outside the faulted zone [9-11]. The decision of generating unit disconnection is determined according to grid code limit curves as shown in Figure 1. Regarding to these curves, the limit line 1(or limit line 2 due to constraints of the plant concept) the generation units must not be disconnect during 150 ms for a voltage dip to 0.45 U_n [8-13]. Below the borderline 2, a short-time disconnection of the generating plant may be carried out in any case [8-13].

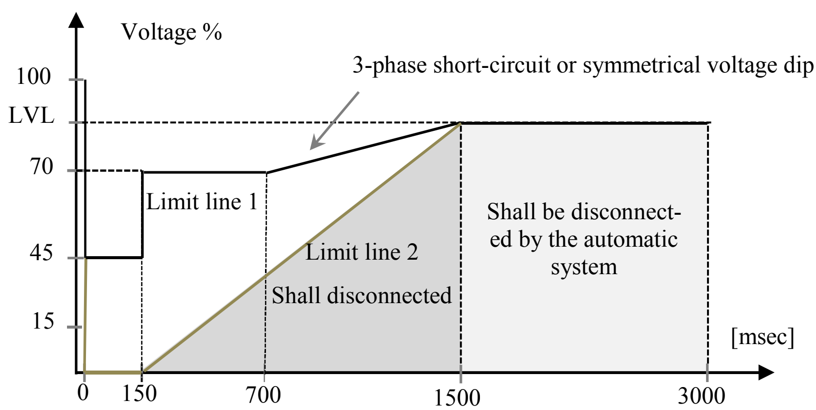

Figure 1: *Voltage limits for disconnection of generating units in the case of grid faults [11, 13].*

All the generation units should support the grid through supplying reactive power current in the case of fault (see Figure 2). The reactive power current provided by the generator should to be at least 2% of the rated current per each percent of the voltage sag. In some cases, the generating unit has to be able to supply a full rated reactive current.

The generators have to be operated and controlled according to the grid code represented in Figure 2. The minimum required reactive power current to be injected is identified by the blue line in Figure 2. To be in the safe side higher reactive currents can be also injected [11, 13]. The voltage support shall be maintained for further 500ms after the voltage returns within the dead-band. The priority for voltage support to recover the voltage is the reactive power, so if needed the DG must be able to reduce the active power generated [11, 13].

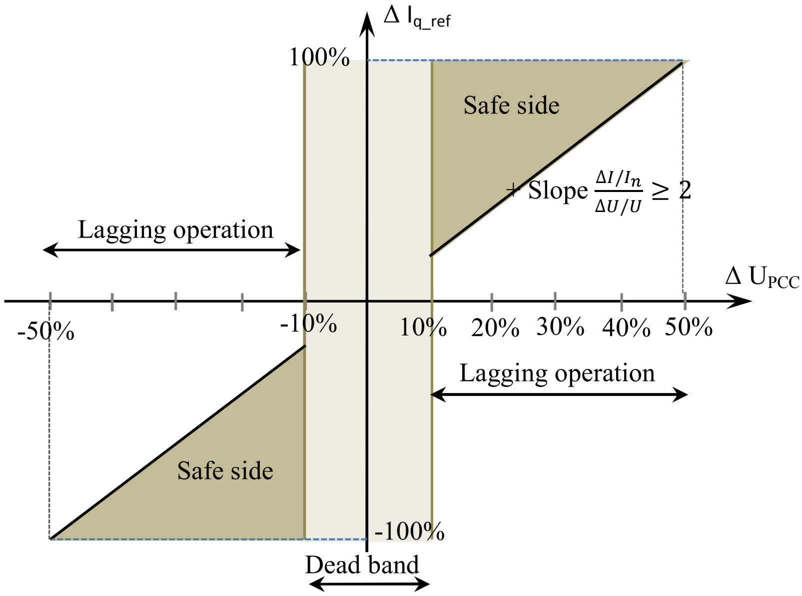

Figure 2: *Amount of reactive current for voltage support in the event of grid fault [11, 13].*

2.2 Irish grid code

Irish distribution code requires the DG to provide current during voltage dips as follows [14, 15]:

(i) Active power is provided in proportion to retained voltage.
(ii) Reactive current is maximized without exceeding generating unit limits.

The maximization of the reactive current shall continue for at least 600 ms or until the distribution grid voltage recovers and be within the acceptable range [15]. The limit curves for the voltage pattern at the grid connection point for fault events are shown in Figure 3 [14, 15].

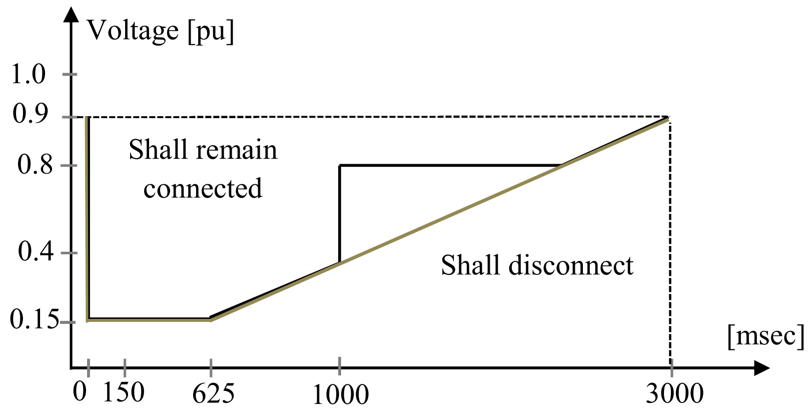

Figure 3: *Fault ride-through requirement for DGs connected to the Ireland's distribution system [14, 15].*

2.3 Spanish grid code

Minimal interconnection requirements for wind turbines connected to the Spanish transmission system have been issued by REE Spain [8, 9] and it was published officially in October 2006. This document is only addressed to fault ride-through capabilities and grid voltage support (i.e. reactive power/voltage control) during faults; it applies to all operators connected to the main transmission grid. These requirements presented by REE are also valid for wind farms connected at the distribution level. The Fault ride-through requirement for DGs connected to the Spanish distribution system is shown in Figure 4.

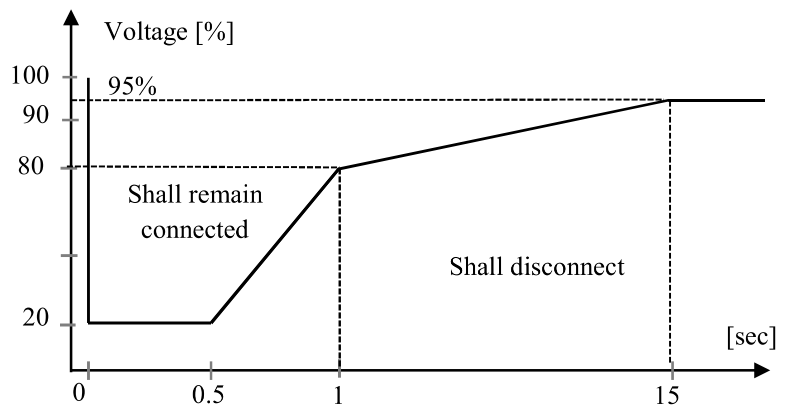

Figure 4: *Fault ride-through requirement for wind turbines in the Spanish transmission grid [8, 9].*

In Figure 5, it can be seen that the grid voltage support by means of reactive current injection is required for a DG voltage below 85% (i.e. voltage dip above 15%); below 50% of the rated DG voltage, a reactive current injection within 90% - 100% of the rated current is required.

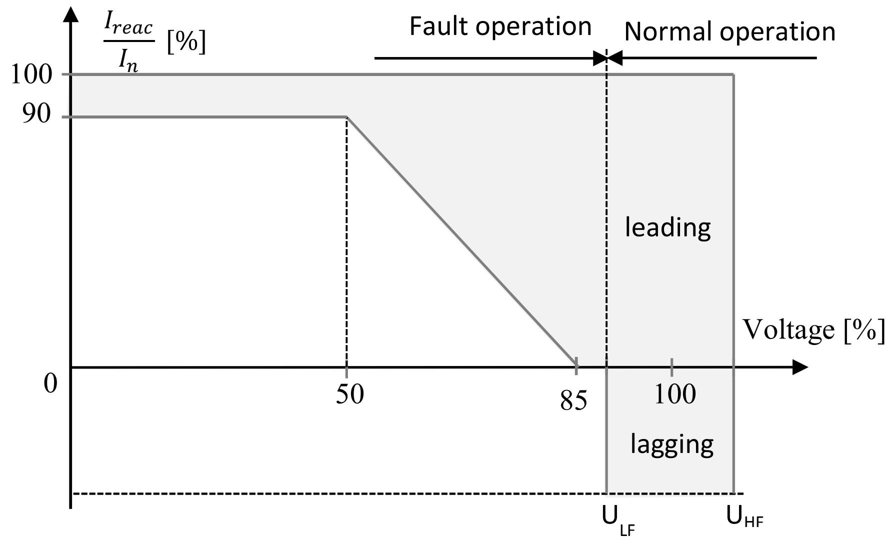

Figure 5: Grid support during faults by reactive current injection as specified in the Spanish grid codes [8, 9].

3 DEVELOPMENT OF THE GRID SUPPORT CODES DURING DIPS

Fault ride through requirement in distribution network is a new issue and less studied before as there were no generation in distribution networks. Most grid codes are discussed FRT requirements for DG connected to transmission network, and recently the same principle is used for distribution networks. The main difference between the transmission and distribution network is the value of X/R ratio. Transmission lines have higher X/R than distribution lines. So the priority is to inject reactive current into the grid during dips in case of transmission lines. In the other hand, in case of distribution network, active currents have to have the highest priority. However, all grid code ignores the importance of active power during dips. Moreover, some codes require curtailments of active current to allow more injection of reactive current. In the next subsection, the effect of X/R ratio on voltage control is discussed.

3.1 Effect of X/R ratio on voltage deviation

This subsection investigates the influence of active and reactive power on the grid voltage. Figure 6 shows a simplified network. The grid is modelled by a voltage source U_s and a short-circuit impedance Z_{sc}.

A constant current load and a DG unit are connected to the network. The voltage at their terminals is U_{dg}. The voltage U_{dg} without DG unit connected is chosen as the reference voltage.

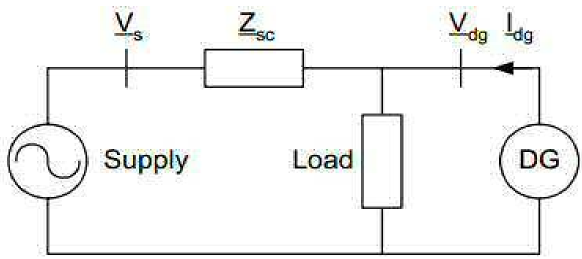

Figure 6: *Network diagram with Thévenin equivalent of grid, load, and DG unit.*

The voltage variation ΔU across the line can be approximated represented by the following equation [16, 17]:

$$\Delta U = \frac{P_{dg} R_{sc} + Q_{dg} X_{sc}}{U_{dg}} \quad (1)$$

where, ΔU indicates voltage variation, P_{dg} and Q_{dg} represent active and reactive power output of DG, X_{sc} and R_{sc} are reactance and resistance of the line connecting to DG, U_{dg} is nominal voltage at the terminal of DG.

Under the assumption that $U_{dg} \cong U_s$, the following approximation holds [16]:

$$\frac{\Delta U}{U_{dg}} = \frac{S_{dg}}{S_{sc}} \quad (2)$$

Considering U_{dg} is reference and equal to 1 p.u., then equations 6.1 and 6.2 represent voltage variation. Generally, compared with transmission line, the X/R ratio is relatively low in a distribution network. According to Equation 6.1, any significant amount of power injected by DG will result in voltage rise/drop on the distribution network, especially in a weak distribution feeder with high impedance. The voltage variation would also depend on several factors including DG size and location [16-18]. Voltage control with reactive power is traditionally applied in the high-voltage transmission grid.

The impedance is dominated by the reactance of the overhead lines and the transformers, offering good possibilities for reactive compensation. At lower voltage levels voltage control with reactive power is more difficult because the line impedance is mainly resistive. In addition the voltage increase due to the active power of a DG unit is relatively large because of the relatively high resistance [16-18].

3.2 FRT requirement in active distribution network

As discussed in the previous subsection the voltage deviation depends on X/R of the distribution lines. However most grid code requires reducing active power during voltage dips and injects as much as possible reactive power to the grid which is Q_{max} of the DGs, we will allow injection of active power as available in the DGs and also allow injection of reactive power. Then investigation between the national grid code requirements and proposed requirement.

The proposed FRT requirements are as following:

(i) Supply the available amount of active power.
(ii) Inject reactive power with the rest of the DG size.

3.3 DG inverter mathematical model

In this subsection, we will write the equations of the German code and then write the equations of our proposed FRT requirements. For DGs which is connected to the grid via power electronic inverter, the output power of the DG inverter can be written as [19]:

$$P = u_d \cdot i_d + u_q \cdot i_q \tag{3}$$

$$Q = -u_d \cdot i_q + u_q \cdot i_d \tag{4}$$

Where

$$u_d = u_r \cdot \cos(\varphi) + u_i \cdot \sin(\varphi) \tag{5}$$

$$u_q = u_i \cdot \cos(\varphi) - u_r \cdot \sin(\varphi) \tag{6}$$

Where: u_d, i_d : is the d-axis voltage and current in p.u.;

u_q, i_q : is the q-axis voltage and current in p.u.;

u_r , u_i : are the real and imaginary part of the voltage at PCC in p.u.;

ϕ : is dq reference angle;

P, Q : is the active and reactive power in p.u.

When fault occurs, according to the German grid code, DG inverter should supply reactive power to the grid. The relationship between the increment of reactive current and the PCC voltage deviation is shown as Figure 2. Where ΔI_{q_ref} is the increment of reactive reference current, ΔU_{pcc} is voltage deviation.

The relationship between the increment of the reactive current and the voltage deviation can be written as [20, 21]:

$$\Delta I_{q\_ref} = K \cdot \Delta U_{pcc} = K \cdot (U_{pcc\_ref} - U_{Pcc\_f}) \tag{7}$$

where U_{pcc_ref} and U_{pcc_f} represent the magnitude of rated voltage and fault voltage at PCC respectively. K is the coefficient of reactive power support. According to German code K >= 2. For simplification, no reactive power would be supplied during normal operation and I_{q0} equals to 0. Therefore, when fault occurs, $I_q = \Delta I_{q\_ref}$. The reactive current increases with the drops of PCC voltage as indicated by equation (7). At the same time, as the PCC voltage drops, the active current of the inverter is controlled to increase, so as to output the reference active power and keep dc voltage constant [21]. However, with the limitation of the short-circuit capacity of the PV inverter, the maximum fault current is about twice of rated current [20, 21]. The reference current of the inverter is limited to 2 p.u., so as to protect the device. To support the voltage, the fault ride-through control strategy of DG controls the reactive power prior to the active power according to German code, which represents that the reactive current would follow the reference value, while the active current would be limited. So the fault current of DG inverter can be expressed as:

$$\begin{cases} I_{q\_ref} = \min(K(U_{Pcc\_ref} - U_{pcc\_f}), I_{\max}) \\ I_{d\_ref} = \min(\dfrac{P - u_q \cdot i_q}{u_d}, \sqrt{I_{\max}^2 - I_{q\_ref}^2}) \\ I_{\max} = 2\,p.u. \end{cases} \tag{8}$$

Equation 8 represents the characteristic equations proposed by the German code. The reactive current is limited by $I_{\max}$, while active current is limited by the rest of the inverter size. It is clear that the priority is given for the reactive current rather than for the active current.

In our proposed FRT requirements in distribution network, active power has the priority to inject during fault rather than the reactive power. The equations of the proposed FRT requirements are as following:

$$\begin{cases} I_{d\_ref} = \min(\dfrac{P - u_q \cdot i_q}{u_d}, I_{\max}) \\ I_{q\_ref} = \sqrt{I_{\max}^2 - I_{d\_ref}^2} \\ I_{\max} = 2\,p.u. \end{cases} \tag{9}$$

Equation 9 shows that the proposed FRT requirements give the priority to the active current and then for the reactive current according to the rest of the inverter size.

4 TEST SYSTEM DESCRIPTION

The simulation model of distribution network was built in PowerFactory DIgSILENT to verify the effectiveness of the proposed control strategy. The model is depicted in Figure 7 [20]. The voltage source = 10.5 kV, with internal impedance Z_s = j2.3Ω, apparent power of the load S = 9.8 + j0.5 MVA. Impedance of Line_2 is twice the impedance of the Line_1.

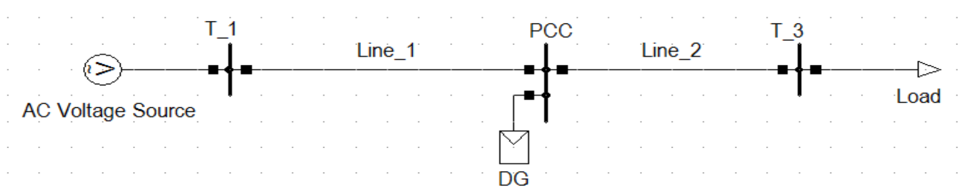

Figure 7: *Single line diagram of test system.*

The lines impedances are changed (Figure 8) to show and evaluate the effect of X/R ratio on the performance of each FRT requirements. The magnitude of the impedance is the same; only the angle between R and X is changed.

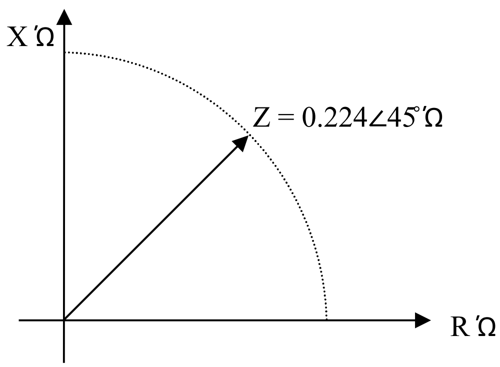

Figure 8: *Line impedance with different X/R ratio.*

5 SIMULATION RESULTS

Both German code FRT strategy and developed FRT strategy are applied on the simple test system. Figure 9 shows the difference in voltage using both strategies at different X/R ratios when the active power of the DG is 0.4 p.u. of the DG size (DG size from 1 MVA to 10 MVA which represents different penetration levels). Therefore, applying the proposed strategy allow the DG to inject reactive power up to 60 % of DG size. At Low X/R ratio the difference the voltage under the new FRT strategy and the voltage under the German code is positive (Figure 9). However, at higher X/R ratio the difference between the voltages is small or negative which mean that voltage dip under German code is higher than voltage dip using proposed FRT strategy.

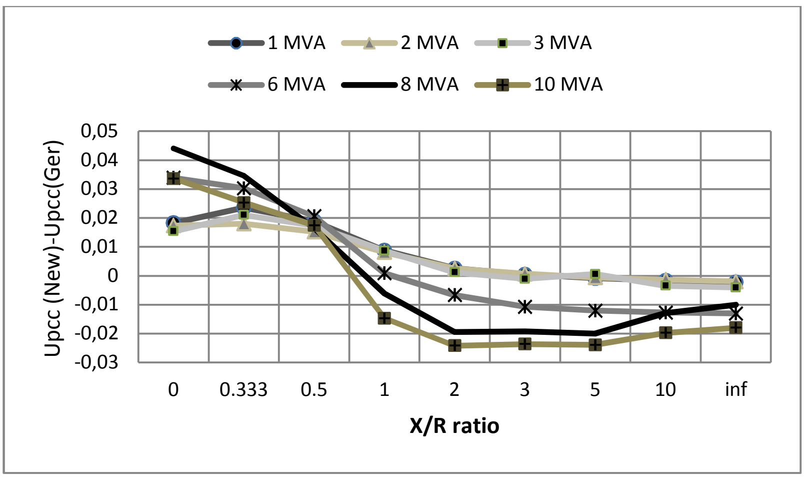

Figure 9: *The difference between the voltage at PCC using new FRT strategy and German code strategy with different X/R line impedances.*

Figure 10 shows the results in case of the supplied power from the DG represent 0.8 p.u. of the DG size. At low X/R ratio, the proposed FRT strategy help to increase voltage dip. With increasing X/R ratio, voltage is reduced and at large X German code strategy has better voltage dip. In conclusion, in distribution network the ratio X/R are small so the proposed FRT requirements are preferred but at transmission network which characterized by high X/R ratio, German code is preferred.

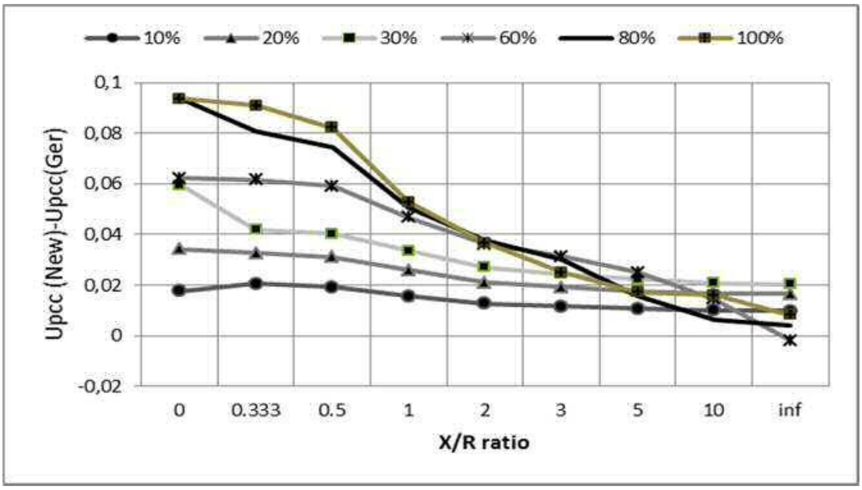

Figure 10: *The difference between the voltage at PCC using new FRT strategy and German code strategy with different X/R line impedances.*

6 CONCLUSIONS

In this paper, a new voltage support control strategy is proposed to improve the fault ride-through capability of converter based DG units taking into consideration the effect of low X/R of the distribution network lines.

The influences of active and reactive powers from DG on the PCC voltage are analysed using the proposed strategy and the German grid code. The following conclusions can be drawn from the results:

- A new approach for controlling the voltage at PCC during fault is proposed and presented.
- Applying the developed FRT strategy at low X/R lines improves the voltage effectively during the fault.
- The developed FRT control strategy can maximize the voltage support capability of DG while takes the safety of equipment into consideration as well.

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TECHNOLOGY &SCIENCE

SPECTRAL GRID IMPEDANCE AND ELECTROMAGNETIC INTERFERENCES IN THE 2 TO 150KHZ FREQUENCY RANGE

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Keywords: Electromagnetic Compatibility (EMC); Grid impedance; Low voltage distribution grid; Renewable energy; Power Line Communication Systems (PLC); Smart Grid; Smart meter; Standardisation.

ABSTRACT

A large scale deployment of Smart Meters is scheduled in Europe and in Switzerland during the coming years. Smart Meters and Smart Grids require efficient communication ways and Power Line Communication System are often considered as the most economic and efficient solution. Electromagnetic interferences (EMI) can occur between PLC and other electronic devices connected to the grid, in particular Active in-feed Converter dedicated to the production and the storage of energy produced from renewable sources.

This article presents a short description of the complex situation with EMC phenomena in the grid in the frequency band between 2 to 150 kHz. The spectral grid impedance has a strong impact on EMI between electronic equipment and Mains Communication Systems. We present suggestions how to support the standardization process with a systemic approach. A measurement method for grid impedance in the frequency range between 2 and 150 kHz is presented. Interference processes can be emulated and analysed at our GridLab infrastructure, a new laboratory dedicated to the integration of renewable energy to the grid.

1 INTRODUCTION AND BACKGROUND

A large scale deployment of Smart Meters is scheduled in Europe and in Switzerland [1] during the coming years. Smart Meters and Smart Grids technology in general require efficient communication systems. Power Line Communication Systems play an important role as a link between end users and concentrators usually located in transformer stations. In this frame, the EMC regulation in the frequency domain below 150 kHz has become a priority for standardization authorities. The 3 to 95 kHz band has been designated by CENELEC for communication systems dedicated to Smart Grid Technologies.

The fact is that electronic charges and sources connected to the grid produce harmonics which interfere with Power Line Communication systems. This is the case in particular with Active In-feed converters dedicated to Renewable Energy production (like Photovoltaic i.e.) and distributed energy storage systems. No emission limits are specified yet in that range for this type of equipment's. The exhaustive study report on EMI published by CENELEC scientific committee SC205 summarises well this situation [2]

New standards for Electromagnetic Compatibility in the frequency range 2 to 150 kHz are needed. Unfortunately the limits proposed by the committees in charge of communication are clearly lower than emission generated today by Active In-feed Converters. Conflicts of interest appeared during the last two years between representative of Power Electronics industry and Smart Grid Industry. Standardization expert groups are working on the subject in Europe. The situation is becoming complex, due to the fact that industry was 'running faster' than standardization. It will surely take a couple of years until a compromise is found and IEC or European standard is published and generally accepted. Coordination by third party and independent experts is necessary. A more systemic approach than the classical 'perturbation emission – immunity levels' is strongly recommended.

The harmonic grid impedance has a great impact on signal transmission and electromagnetic interferences. EMC testing Standards for equipment usually refer to grid impedance at fundamental frequency (50Hz) [3] or recommend using standardized Line Impedance Stabilization Networks [4] with values higher than the ones measured in European distribution grids [5]. We suggest giving in the future more importance to the spectral grid impedance in the 2 to 150 kHz EMC standardization processes. The prototype of a new On-Line Grid Impedance Meter for this frequency range has been realized at HES-SO Valais Wallis. A laboratory infrastructure dedicated to grid integration of renewables the GridLab has been implemented at our facilities in Sion. This paper describes how we plan to use the grid impedance measurement methodology within the GridLab infrastructure.

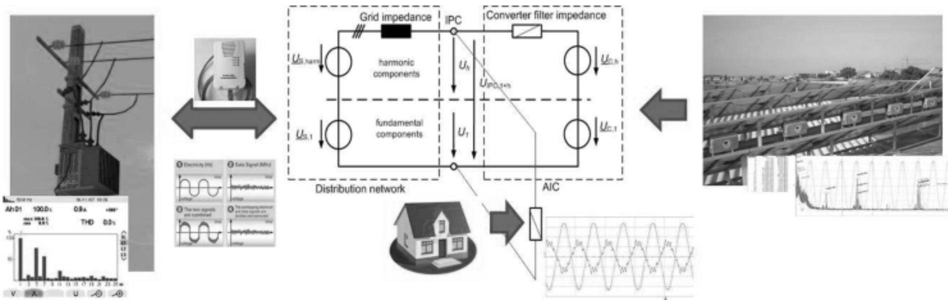

Figure 1: *Systemic approach for the EMC standardisation in the frequency range 2 to 150 kHz.*

2 THE ROLE OF GRID HARMONIC IMPEDANCE IN THE PROPAGATION OF ELECTROMAGNETIC INTERFERENCES

The role of grid impedance in case of EM perturbation by active in feed converter is described in the TS 62578 Ed.2 Technical report by IEC technical committee TC 22 [5]. An equivalent circuit for the interaction of the power supply system with an AIC is represented at fig 3 of that document:

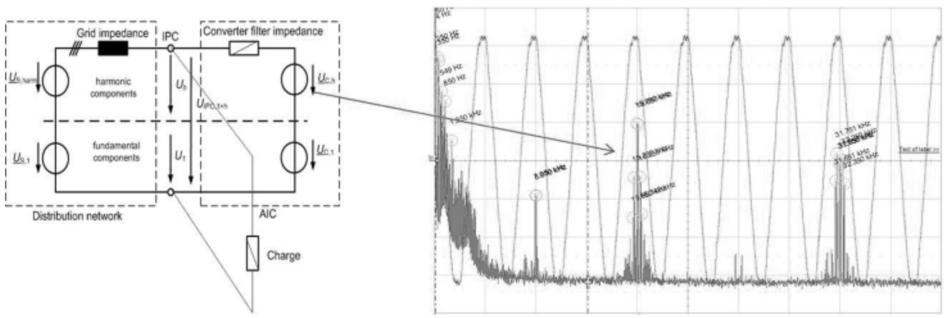

Figure 2: *Simplified schematic representation for Harmonic emission and propagation on the grid. (5kHz/div - 10dBuV/div).*

The non-intentional signal emissions due to the Pulse Width Modulation patterns of a PV inverter are represented on the right of figure 3. Harmonics generated by active in-feed inverters can reach up to 120dBuV at frequencies between 8 and 80 kHz. The ‘supply side filter impedance’ is due to the EMC filter usually realized with passive components (LCL, CLC, LCL trapped filters, i.e.).

The ‘supply impedance’ corresponds to the sum of the distribution grid lines and transformers impedances. It is usually inductive. The represented circuit can be considered as a voltage divider. The values of the equivalent circuit impedances Z_h at the frequency F_h of the undesired harmonics will determine the ratio between harmonic voltages at the point of common coupling (PCC) and harmonics generated by the inverter:

$$U_{h,PCC} = U_{h,inverter} \cdot \frac{Z_{h,grid}}{Z_{h,grid} + Z_{h,inverter}} \quad (1)$$

The PLC communication signals emitted from a smart meter can be at a frequency close to the voltage harmonics generated by the inverter (ca. 37 kHz for instance). The considered signal is more likely to be disturbed when the output impedance of the inverter is low in comparison with the impedance of the grid. This problem is generally solved by implementing EMC filters with high impedance at the frequencies of the harmonics generated by the converter. Today's effort in EMC standardization processes is generally pushing towards that direction.

3 IMPACT OF HARMONIC IMPEDANCE ON PLC TRANSMISSION

As explained before, Harmonic voltages generated by converters can actively interfere with PLC signals. However, EMC filters interfacing electronic devices to the grid can affect PLC communication by notching effects. These effects can be foreseen and analysed on the basis of the measured or calculated spectral impedance seen from the grid side. Due to the parallel and/or series resonances of LCL filters, the impedance seen from the grid side varies in function of the frequency. The figure hereafter shows the theoretical impedance of a CLC filter for electronic ballast, as seen from the grid side.

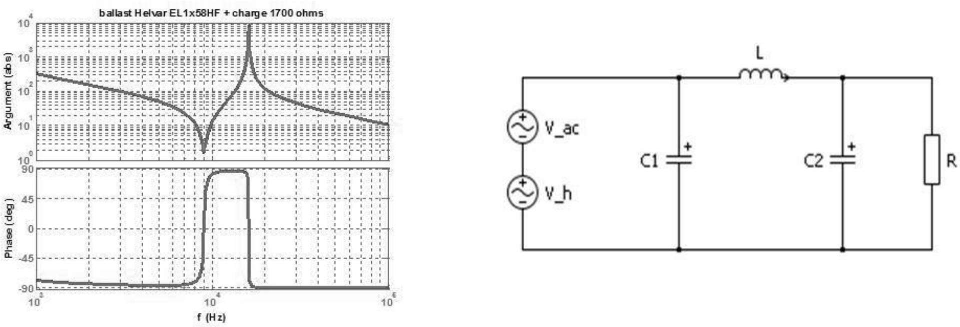

Figure 3: *Grid Impedance for the input filter of an electronic lighting ballast: spectrum and circuit.*

The frequency analysis shows extremely low impedance at the frequency of the series resonance effect. It is very likely that a PLC signal at a frequency close to that frequency will be filtered out by so-called notching effect. This effect will be stronger when the grid side impedance of the filter is low, which is the case with C-L-C filter topology. If needed, attenuation factor of EMC filters is usually improved at lower cost and higher energy efficiency by increasing the capacitance value in the filters. We estimate that notching effects on MCS will increase if better filtering of harmonics generated by converters is required.

Other power quality components than EMC filters for electronic devices can have similar effects on grid impedance: large capacitors for VAr compensation for instance. The previous examples are based on EMC filters with passive components.

Similar effects can be generated by the active filter systems, including harmonic compensators or Active In-feed Inverters. The inverter output impedance seen from the grid side is strongly affected in the frequency domain by the inverter controller topology and parameters [6]. These phenomena usually affect the lower side of the considered frequency range, from a few hundred Hertz to a few kHz.

Our recommendations regarding emissions reduction through passive EMC filters are the following:

- Interaction of converters and EMC filters with the distribution grid, which are leading to a reduction of the grid spectral impedance should be studied more carefully. A particular attention should be given to resonances effects.
- A more systemic approach is needed, which does not only consist in setting lower limits for emission generated by individual electronic equipment in laboratory conditions.
- EMC filters should be dimensioned or configurable in function of the number of inverters connected in parallel and in function of the grid specific conditions in the application.
- Efforts to limit EMI should take into account possible counter-effects linked to spectral grid impedance. Filter topologies which can reduce or increase spectral impedance below or over certain limits should be avoided.

Further statements can be made on the basis of SC 205 EMI Report TR50627 Ed. 2, IEC TC 22 report TS62578, literature and results of measuring campaigns in laboratory or on PV production sites:

- Each electronic equipment connected to the grid has its own EMC filter with own resonance frequencies. Connecting several equipment in parallel results in a damping effect on resonance (positive effect). But resonance frequencies will be shifted. If these equipment's are turned on and off, the spectral impedance for a system becomes unpredictable in time. [7, 8] In some cases inverters will include adaptive controllers, which makes the situation even more complex.
- It is usually not possible to estimate the harmonic impedances for complex systems on the basis of calculation. Measurement and simulation in frequency domains are required. [9]
- The grid impedance measured on several distribution grid in France and Germany show a significantly lower impedance than the impedance recommended in standards (IEC 61000-4-7 for instance [4]). Using this impedance values in laboratory tests would lead to overestimation of disturbances. This would result in a long term to a reduction of voltage harmonics generated by equipment, but on the other hand, the risk of a stronger attenuation MCS signals.

- Harmonics present on the grid generate an accelerated aging effect on filter capacitors. Damaged capacitors will result in shifting filter resonance and cutting frequency or even worse in cancellation of any filter effect. [5].
- The frequency of the harmonics generated by AIC will increase during next years: new power semiconductors technologies available on the market (SiC, Gan, etc) will allow faster switching frequencies with low power losses.

4 ON-LINE GRID HARMONIC IMPEDANCE MEASUREMENT

Understanding the key role played by harmonic grid impedance in the EMC phenomena, several academic institutions and companies have developed On-line spectral impedance meters based on different approach. At this time, few of these equipment's are commercially available and none fully satisfies the needs for research and standardization in this domain.

The IGOR project was initiated at HES-SO Valais Wallis a few years ago, with the scope to investigate on Interferences Generated by Inverters on the Grid. In the frame of this project we started the development of an instrument dedicated to the On-line measurement of Grid Impedance between 2 and 150 kHz. Measuring campaigns showed that harmonic currents circulating between two inverters increase when the frequency of the harmonics correspond to a serie resonance frequency of the second inverter's EMC filter [9]. It is shown in [8] that inverter controller stability is lower when the grid line impedance increases. In this case, the spectral impedance at the frequency corresponding to the poles of the controller can have a much more serious effect than the impedance at fundamental frequency. This is what we aim to investigate with the help of the Spectral impedance meter.

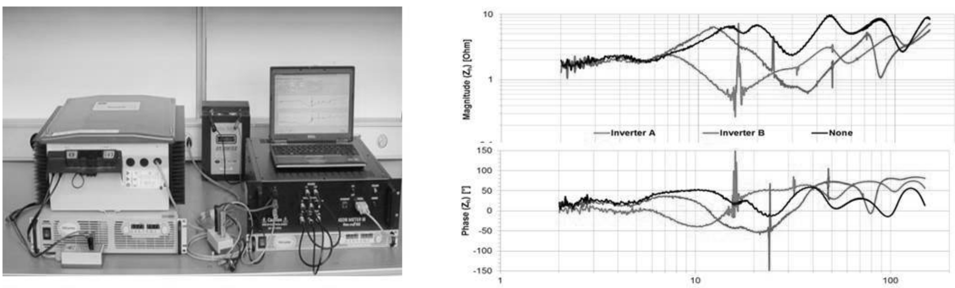

Figure 4: 2 to 150 kHz On-line Grid Impedance meter and test results on PV inverters.

The first prototype of the so-called IGOR-Meter was conceived with emphasis on the following features:

- Low impact on the measured grid
- Large frequency range
- Good accuracy in phase and amplitude
- Phase to neutral measurement (L-N)

- Easy to transport
- Reasonable costs

A new version of the impedance meter is under development at HES-SO. The new equipment should be more robust, faster and have a more flexible user's interface. It should be easily transportable and have sufficient autonomy to serve week long measuring campaigns.

5 PRE-STANDARDISATION ACTIVITIES AT GRIDLAB DISTRICT

The GridLab District at HES-SO Valais is a full scale experimentation platform dedicated to research and teaching activities in the field of renewable energy sources and storage integration into the grid. A three phase 400Vac feeder to which loads and sources are connected is at the heart of the GridLab District platform. For better efficiency and increased flexibility, consumer's loads, production plants and storage systems are emulated with the help of static converters. A state to the art communication system allows data exchange between converters and a centralized control unit. Real loads, storage units and a photovoltaic production plant complete the GridLab District for components testing and evaluation.

Figure 5: *Panoramic view of the GridLab infrastructure at HES-SO Valais Wallis.*

The figure hereafter illustrates one GridLab District 'Street unit' in one of its application: the emulation of a street feeder with three distributed energy producers along the line. Each house is emulated by a 4Q converter. Active and reactive power used or produced by the three houses on the right can be remote controlled. In a typical scenario, reactive power absorbed by the 'pro-sumers', will keep the line voltages within the limit accepted by the local grid code. The line voltage variations measured by smart meters and power setting values are transmitted to the district control unit through IEC 61850 based communication protocol. Optimal control strategies can be implemented and evaluated at the level of the control unit.

The infrastructure of the GridLab DISTRICT is the perfect tool for the evaluation of Electromagnetic Interferences (EMI) between active infeed inverters and Power Line Communication systems. The district unit allows the measurement of harmonic currents generated by Active In-feed Converters, as well as the harmonic voltage resulting at the PCC. Variation of the harmonic impact can be observed with one, two or three similar inverters located at different distances from the PCC and working at adjustable power

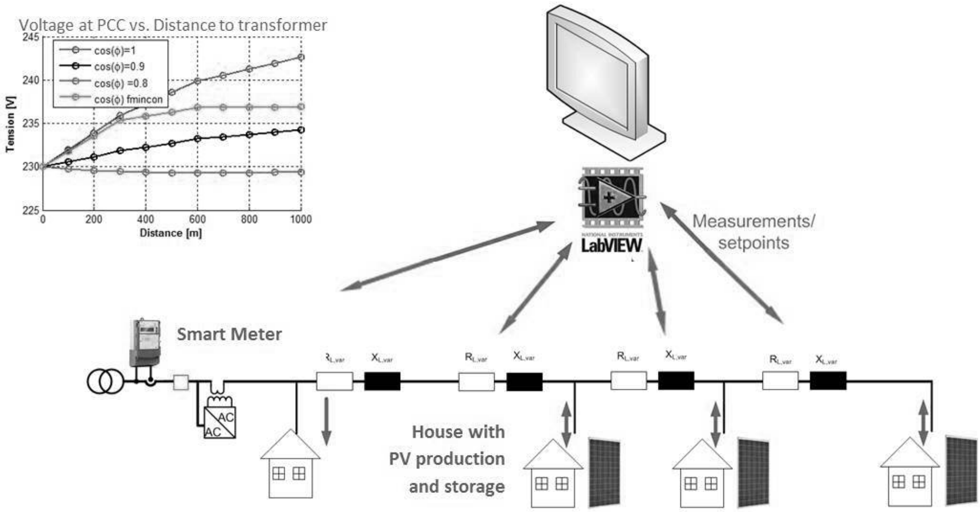

Figure 6: GridLab District Street unit and line voltage control scenario.

In the case of the District Unit, pro-sumers are emulated with industrial converters, with specific harmonic rejection in the frequency range below 20 kHz. Lines and cable are emulated with inductance and resistance.

For the analysis of EMI between AIC and PLC, we plan to insert Smart Meters with communication based on PLC at the coupling point for each house emulator. Emulated line sections can be replaced by real cables of different types. PV inverters from the market can be added at specific coupling points in the circuit.

6 CONCLUSION AND PROPOSED ACTIVITIES

An overview of EMI processes between active in-feed inverters and power line communication systems in the frequency range between 3 and 150 kHz was presented. The spectral grid impedance can be considered as a useful tool for the analysis of the EMI process. We propose to investigate the follow aspects of EMI between inverters and Power Line Communication Systems in a systemic approach:

- Analysis of interference processes based on measurements done at the Gridlab and other laboratory infrastructures affiliated to the DER-Lab association
- Developing and testing further methods and equipment for the measurement of spectral grid impedance
- A system modelling and simulation in time and frequency domain
- Development of control algorithms for AIC which allow a reduction of harmonics rejection without enforcement of passive filtering

Finally, the developed methods and tools should help us defining optimal grid and production plants configurations in order to achieve lower EMI between inverters and PLC systems. This would also allow us to take an active role in the EMC standardisation process, through recommendations for the grid specification and emission levels.

7 REFERENCES

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