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Supporting transient stability in future highly distributed power systems

Abdullah Swissi Emhemed, Ryan Tumilty, and Graeme Burt
Institute for Energy & Environment-University of Strathclyde
e-mail: abdullah.emhemed@eee.strath.ac.uk
UK

1- Introduction

Traditional power systems are under a big pressure by facing the short and long term future energy needs. The pressure is driven by the possible rapid increase in the global demand, the international growing awareness of the environmental impacts due large-scale thermal generating units, and the international concern about the limitation of global primary energy sources. In addition, there is an increasing attention on reliability and security of power systems to minimise the frequent of the recent major blackouts occurred at different parts of the world in the last decade while dealing with aging infrastructure [1] - [9].

To deal with such challenges, the traditional power systems would expect to experience profound changes. For example increasing the level of the efficiency across the power system sectors including production, transmission, distribution, and consumption will play a very significant role in reducing the system losses and at the same time saving energy sources for the future [10]. According to International Energy Agency (IEA) statistics, 16% of the global CO₂ emissions increase since 1990 caused by the energy use alone [11]. Taking the UK as an individual example, approximately 25% of the country greenhouse gas emissions caused by the heat and electricity usage at residential sector [12][13]. Therefore, a domestic sector has a significant impact on climate change, and also if the right measures are applied to the sector, it would play a significant role in reducing GHG emissions, and reserve more energy primary resources. Therefore, encouraging the wider usage of renewable and low carbon energy generation and being integrated at distribution and at electricity use points will reduce the carbon emission as well as providing other ancillary services that can support the system. The change in the domestic energy use from uncontrollable to more manageable demand, the connection of small scale embedded resources such as microgeneration, and carbon lean transportation will limit the energy waste and provide a significant efficiency improvement [13]. In addition the heat generated by decentralised electricity production can be used for space and water heating [13]. The potential impact of plug-in Electric Vehicles would offer spinning reserves and some ancillary services [14].

Therefore, there is a drawn international attention to set a target to provide a significant amount of the electricity generation from renewable and highly efficient energy sources. As an example, the UK and other European governments have set a demanding target to provide considerable amount of their electricity consumption from such forms of energy sources [15][16]. In addition the renewable portfolio standards (RPS) which is provided by the US Environmental Protection Agency have establish requirements for electric utilities and other retail electric providers to serve a specified minimum percentage or absolute amount of customer consumption with eligible sources of renewable electricity [17]. The EU is aiming to make the share of renewable energy sources (RES) to provide EU electricity to reach 20% of energy in 2020, and the figures would be increased to 60% by 2050 [18]. Alongside the EU, the UK government has set mid and long-term national targets which aim to cut CO₂ emissions by 26% by 2020 and up to 80% by 2050 compared to 1990 levels, and renewable and low carbon energy sources are expected to significantly contribute to meet these targets [19][20].

The present power systems are not designed for accommodating such considerable amount of new energy sources connected at distribution levels [21]. This will evidently require a radical change in the system structure as well as the system performance under different operating conditions. Due to the prediction of the increased number of microgeneration along with other distributed energy sources (DERs) such as dynamic loads and storage devices, and since these technologies would be applied to distribution systems, the changes that are happening in the electric power systems would be particularly significant for the electricity distribution grid [22].

However, distribution networks are traditionally designed and viewed as a passive portion of the grid system with very limited automation and controllability. Their main tasks are to deliver the available

electricity from the generation and transmission systems to the growing demand of the electricity users without expecting any participation from the users to the system operation. Consequently, distribution networks are under a large pressure to be reconsidered in order to accommodate such changes. The study commissioned by the Department of Trade and Industry (DTI) of the UK from the Energy Saving Trust has suggested that 30-40% of the UK's electricity demands should be met through microgeneration technologies by 2050 to meet the UK's 2050 target, with combined heat and power (CHP) leading the way, followed by micro-wind and photovoltaic (PV) [23]. This is based on the numbers of different future scenarios studies such as in [24][25] which expected microgeneration to have the potential to encourage the public to generate their own electricity [26], and also the potential to reduce losses associated with producing and delivering electricity, and combating climate change and fuel poverty, as well as improving the overall system efficiency.

It was concluded in [13] that an extensive uptake of microgeneration is required to significantly provide such useful contribution to local and wide system, and the access for the consumers to install their microgeneration in their millions should be provided. Incorporating a substantial volume of microgeneration driven by consumers choice and not centrally planned within a system that is not designed for such a paradigm could lead to operation at cross purposes between these new added technologies and the existing centralised generation. So it becomes vital for such substantial amounts of microgeneration among other decentralised resources to be controlled in the way that the aggregated response will support the wider system. In addition, the characterisation behaviour of such penetration requires to be understood under different system conditions to ascertain measures of risk and resilience. Therefore, this paper provides two main contributions: Firstly, a conceptual control approach for a system incorporating a high penetration of microgeneration and dynamic load, termed a Highly Distributed Power System (HDPS), is proposed. Secondly, a technical solution that can support enhanced transient stability in such a system is demonstrated.

The proposed approach of control with a HDPS is based on managing the distributed energy resources within multiple "cells". This structure supports the effective exploitation of vast population of microgeneration, demand response, storage, and plug-in electric vehicles such that system services & load constraint mitigation can be delivered with decentralised market framework. The paper will demonstrate the benefits of this structure to deliver smart grid functionality.

The connection of a large number of microgenerators within a cell will significantly alter its transient behaviour and requires careful consideration. Therefore, the paper also describing device focussed and network focused technical solutions by which the transient stability of such technologies within a cell structure is improved. The solutions are based on using resistive type superconducting fault current limiters (RSFCLs) as a remedial measure to prevent substantial amounts of microgeneration from being unnecessarily disconnected due to remote faults. Because such disconnection could lead to a sudden appearance of hidden loads, unbalanced voltage conditions, and reducing the significant contribution of microgeneration such as tackling climate change and the customer's interest in considering microgeneration as reliable energy sources.

2- Highly Distributed Power System (HDPS) & Cell concept

Highly Distributed Power System is a system that is incorporated with a significant penetration of microgeneration and dynamic load, in the way that the loads would be supplied by a wide range of generation landscape. The HDPS concept can be summarised by the statement "many active loads – many sources", in contrast to the traditional systems with "many passive loads – few sources".

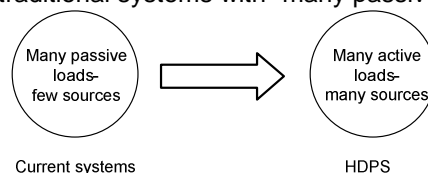


Figure 1: Moving towards power systems with many loads supplied by many sources
From the structure perspective, the HDPS can be divided into multiple manageable areas which are termed as "cells", so the system can be seen as an aggregate body of multiple cells with different

boundaries and different functions based on the required objectives and the cell capabilities to manage multidirectional power and information.

The HDPS cell is based on the concept that distribution networks will be characterised by numbers of manageable areas that have their own characters and can govern their own local constraints, and at the same time meeting external needs. The cell is defined based on the growth of numbers of microgeneration and other distributed energy resources such as dynamic demand response, storage, and plug-in electric vehicles within a given distribution area. The cell should be capable of managing the impact provided by these devices within its boundaries and at the same time capable of passing the collective impact to a higher system level beyond its boundaries if required to support wider system. In addition, the cell also should be capable of being able to operate in conjunctions with other adjacent cells to form a bigger cell in hierarchal structure that will significantly support wider system up to transmission level [27].

Based on HDPS cell definition, the cell would have two main types of objectives to meet. One is an internal to manage local constraints, and the other is external to export actions for wider system support. The hierarchical structures of cells would be the mechanisms that manage the flows of the actions between cells, based on at which system level the actions are required. Within the structure, exporting actions can be directly from the cell to a larger cell as a combination effort from cell's active elements, or the cell is combined with other cells and the actions are exported further for bigger objectives as a combination of collective cells as shown in Figure 2.

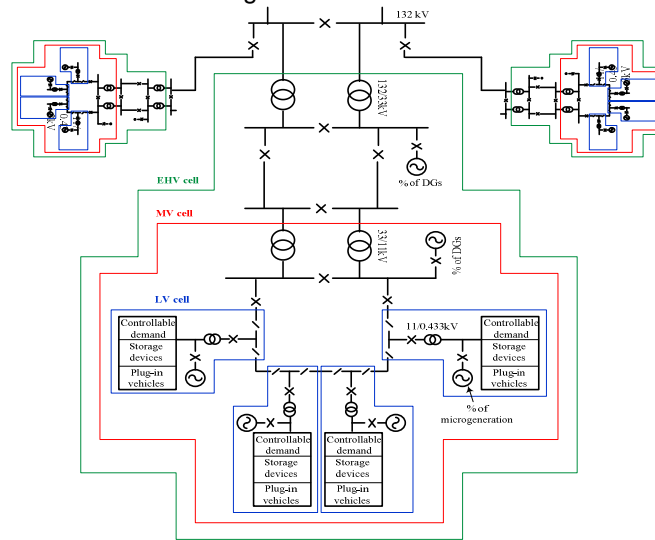


Figure 2: Cell structure examples for urban networks

The characteristics of the cells depend on their boundaries which can be classified by networks layout. The boundaries could start from grid supply point (GSP) at EHV or HV level, MV, or LV levels down to end users points. Figure 2 shows demarcated areas of urban distribution networks as examples of numbers of cells that are formed in hierarchal structures.

2.1 Cell Technical Objectives

The capability of cells to perform certain functions to meet the predetermined objectives can differ from one cell to another. This would be driven by different factors such as the boundaries, level of integrated technologies such as communication systems, smart meters, distribution automations, demand side management, and distributed generation. The functions also would be governed by other factors such as applied regulations, and available market mechanisms. From technical perspectives, the cell would have a range of local and external objectives to be achieved.

The main internal objectives of the cell are to manage the local constraints by accommodating the useful input from all elements such as dynamic demand, storage, and connected microgeneration. For example,

quick and flexible reconfiguration within the cell would improve the outage restoration time, and improve quality for the users. Also an effective energy management within the cell will improve energy usage efficiency, and hence will lead to reduce peak demand. The local active elements of the cell could be used to improve the voltage profile across distribution buses, and the mechanism for such devices to behave in optimised manner can be provided. The internal objectives of the cell could also include the local disturbance management and at the same time reducing the impact of the local disturbances on the wider system.

The cell external objectives are system objectives rather than cell level objectives. Some examples of external cell objectives are for instance, control thermal constraints, and the spread of disturbances such as fault level increase and transient stability problems. Also the cell could provide a collective input to support the system voltage and frequency control, improve the wider system stability, increase generation reserve power, and release the system capacity, and minimise the complexity.

2.2 Control Structure of the cell concept

Based on the cells boundaries, the control structure of cells can be mainly build in hierarchical form to maximise the useful inputs and outputs of each aspect of the system. So the actions can start from a single smart device up to system level, and from the system level down to device level as shown in Figure 3. The control approach within HDPS cells then can be divided into four levels; smart device control level, smart dwelling control level, cell control level, and multi cells control level.

A- Smart device control level

The device control would control the smart device, such as controllable load, microgenerator, storage and plugged-in electric vehicles within a smart house based on the instructions received from the higher level control.

B- Smart dwelling control level

It has two functions: Firstly, making a local decision at customer level based on using local measurement and received control and price signals to meet consumer aims. Secondly, responding to requests from local cell level control whenever are required for larger level targets.

C- Cell control level

This level controls a numbers of active elements within the cell such as microgeneration and dynamic loads in order to meet local objectives of the cell. Also an aggregated corrective action can be extracted from the available collective distributed resources within the cell for local purpose or being exported to wider system level.

D- Multi cell control level

It is multi-level decentralised control that can provide multi-level corrective actions with respect to system operating conditions. The control at this level can be considered as an approach to perform administrative tasks to distribute the management and control tasks of numbers of cells in order to provide significant support to wider system in hierarchical structure.

Within the HDPS cell structure, moving from bottom (i.e. consumer level) up towards system level makes the controls moving to have more relative central functionality. This would be useful in reducing the complexity where the cell would be seen as an aggregate body. The impact of this body is sent in collective form, and this could reduce the number of communication paths. On the other direction when the signals travel from top down to consumer level the structure is moving to more distributed and decentralised approach. This would maximise the chance to include the contribution from most of the network elements as well as reducing the impact a single failure that may result in complete failure of the control system and leads to blackout as in centrally controlled power systems.

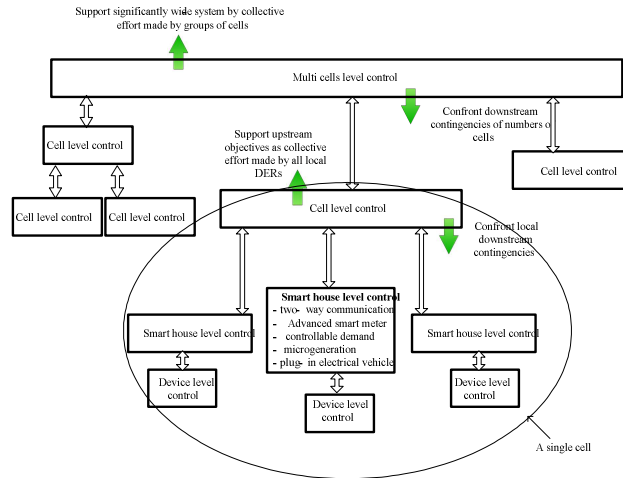


Figure 3: Structure of control levels of HDPS cells concept

Based on HDPS cell structure, and on the projection of forward looking power network scenarios regarding the substantial amount of microgeneration that would be needed in order to meet the future power system targets as discussed before, the cells as small active distribution areas have to be well studied and well understood under different system conditions to ascertain measures of risk and resilience levels. This can help to manage local constraints and at the same time prevent the disturbance to be spread to other adjacent cells or to higher system level.

3- HDPS Cell under disturbances

Traditional distribution networks are radial in nature, and approximately 75% of customers' hours off supply are due to faults on distribution networks [29]. The presence of microgeneration may emerge new technical issues which may stress the network beyond its capabilities. For example, during fault conditions both microgeneration and the host network are under stress. Microgeneration would provide new paths of fault current, and the host distribution system has been designed without the existence of such paths. From the other angle, the host network performance during faults would significantly impact the fault ride through capabilities of microgeneration. A number of previous studies have investigated the technical issues surrounding the connection of a large number of microgenerators in small areas of network such as a new build housing development. The studies such as those reported in [30] and [31], amongst others as in [32] and [33], are extensive in scope and cover issues such as those concerning fault contribution and voltage regulation. The studies were primarily aimed at addressing steady or pseudo-steady-state conditions and did not explore the transient response to be expected from microgeneration.

3.1 Microgeneration transient stability issue

Faults on the system will cause sustained voltage dips resulting in dynamic loads and generators stability issues. If instability occurs, sensitive elements such as microgenerators with low inertia can be tripped, and dynamic loads can be stalled. The studies conducted by the authors in [34] and [35] have concluded that the transient stability phenomenon of microgeneration is a significant issue due to the nature of the units where they have very small inertia and limited controllability. The characteristics and the performance of the existing distribution systems would not be sufficient for supporting the fault ride capabilities of a high penetration of microgeneration connected at LV distribution level. The results of [34] and [35] have shown that local LV faults would have less impact on the transient stability of a large penetration of microgeneration compared to remote faults at MV. This is because during the local faults, the grid fault contribution at LV ensures fast fault clearance by operating the various fuses located on the network. This will lead clearing the fault within few milliseconds, and consequently tripping of microgeneration due to instability will not occur except in the cases where the fault is either at the terminals or in the service connection. Even if the local microgenerator is disconnected the impact would be only losing a single generator or in worst case very limited number of microgenerators nearby.

The transient stability of microgeneration is detrimentally affected due to remote faults on MV side. Remote faults can cause serious disturbances on the microgeneration and lead to massive disconnection

of the domestic size microgenerators connected downstream at LV level. This is because of two main reasons. First is that transient faults on the MV system will cause large voltage dips on the LV system which in turn result in widespread of instability performance of microgeneration. The second reason is the CCT of LV connected microgenerator in response to remote MV fault is relatively small, and if compared to the typical performance of the protection devices at MV level which may take few hundred milliseconds to clear the faults, the microgenerators would be disconnected before the fault can be cleared.

As consequences of remote faults on MV distribution networks, almost simultaneous nuisance tripping of LV connected microgeneration would be experienced. This in turn would impose numbers of issues including the result in impaired quality of supply to the users due to voltage fluctuation during simultaneous disconnection by remote faults or during reconnection of a high penetration of microgeneration. Any deviation out of the nominal limits of the voltage or frequency at the point of supply is not acceptable. This was evidently noticed by the authors in previous studies, where a source of interference with the local system performance under certain conditions as consequences of transient instability of microgeneration can be observed [34][35]. In addition, unnecessary and unplanned disconnection of microgenerators privately owned will be unacceptable, and this can impact customers' interest in considering microgeneration as reliable and sustainable energy sources. From environmental perspective it would lead to losing the significant contribution of microgeneration to tackling climate change even for short period of time. Furthermore, within deregulation power market structures, undesirable disconnection of microgeneration driven by consumers' choice may directly lead penalty compensation to the users that suffer from the blackout or losing their generators due to system faults. Microgeneration can also play a significant role in supporting the performance of the local and external cell objectives.

Therefore, a remedial measure by which the impact of remote faults at the MV level on the microgeneration transient performance is reduced would be indeed vital in order to help the cell to overcome large disturbances. The measure should be a network solution focused rather than a single device focused. This is because microgenerator is very small device with small inertia and limited controllability, so any individual device solution would have small useful inputs limited at the device level. Therefore, this paper proposes the using of Resistive-type Superconducting Fault Current Limiters (RSFCLs) as remedial measures to improve significantly the remote MV faults ride through capabilities of a large penetration of LV connected microgeneration. The limiters would perform the transient stability improvement to downstream microgeneration as a collective group of generators and at the same time limit the widespread of the remote fault and not to go downstream.

3.2 Using the RSFCL for improving transient performance of LV distribution networks incorporated with a high penetration of microgeneration

In terms of improving the transient performance, there are number of solutions have been proposed and developed by different researches. Some research such as in [36] and [37] have explained that any measures reducing the rotor acceleration or regulating the generator terminal voltage during the fault will improve the machine transient response. However, most of the measures that have been developed to enhance the transient performance of rotating machines as documented in numbers of articles are suitable for large distributed generators. However, if RSFCL is equipped at the right location, one limiter could provide a significant transient stability improvement to large amount of microgeneration of wide areas of distribution networks. Also the superconducting limiters are self-operated devices controlled by the condition of the currents pass through them. The limiters provide almost zero impedance during normal operation, and its impedance is developed as a limitation element during fault conditions. The limiters can react within milliseconds, and this is necessary for an improved transient response.

The superconducting fault current limiters can be either inductive or resistive types, but resistive devices (RSFCL) have an added advantage of currently being more available for commercialization [38]. In addition RSFCL has less heat management, and it is more compact to be installed in urban and suburban distribution systems [39]. This could be an important point where space is expensive or difficult to obtain. Also the RSFCL not only restrains the fault currents but also consumes electrical energy during the fault by suppressing the excessive kinetic energy of fault-contributing generators [38]. The RSFCL increases the decay speed of the fault current, and it can also make the system less inductive [40]. Therefore,

RSFCL is considered, and its effectiveness on the microgeneration transient stability performance is tested in details in the next section. It is assumed the limiters to be installed within MV distribution networks as shown in Figure 4 to enhance the transient response of large numbers of LV connected microgenerators subject to remote faults within the system. In addition, the RSFCLs as shown in Figure 4 will manage the fault level between the LV cells.

4- Simulation studies of RSFCL application for microgeneration transient stability enhancement

4.1 Test network model

The test network shown below in Figure 4, and induction microgenerators models that are developed by the authors in [34] and [35] are used in the studies. The network model is developed by using PSCAD/EMTDC. The model is based on customers representing a distribution area of residential dwellings connected to 33kV system. Source impedances are set to provide a typical fault level of 150MVA at the ring main unit (RMU) supplying the secondary substation. An impedance of 4.5% and rating of 1MVA have been taken for the secondary substation transformer. The network is also equipped with numbers of Resistive type Superconducting Fault Current Limiters (RSFCL) and located between the MV bus and the MV outgoing feeders as shown below.

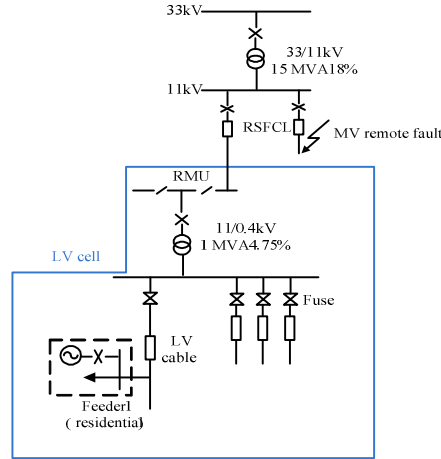


Figure 4: Test MV/LV distribution network incorporated with RSFCL

4.2 RSFCL Model

The limiter is modelled to take actions at the instant of the fault to limit the first peak of the fault current when the fault current exceeds the threshold value. The threshold value of the fault current to initiate the RSFCL is chosen to be larger than the twice of the full load current which is normally considered as the minimum required current for relays to operate. In the studies the threshold value is set to be 3 times of the full load current. When the limiter operates during the fault, a nonlinear resistance will be developed within the path of the fault, and the change in the resistance values is a function of the fault duration. The nonlinear resistance curve is taken from the reported laboratory experimental results in [41] defining the non-linearity of a network-scale RSFCL. RSFCL in each phase is modelled by using two variable resistances connected in parallel as shown in Figure 5. One of the resistances is used to represent the change of RSFCL from super to limiting mode (i.e. R1), and the other represents the characteristics of the limiter during the fault (i.e. R2). The resistances are used to overcome of the limitation in the software. Within the master library of EMTDC only circuit breakers are available to be used as switches. These breakers will operate only at the zero cross points, and they can not represent the RSFCL operation before these points. Therefore, R1 is used instead of using a switch in order to get the limiter actions regardless the first zero cross points. When the fault current exceeds the activation value, R1 will be changed from zero to an open circuit, and R2 develops non linear values according to the values obtained from [41]. For simplicity reason, the permissible temperature rise of the elements is not considered in the model, and it is assumed to be constant. Also because the faulted feeder will be disconnected by the main breaker as shown in Figure 4, the recovery time will have no impact on the system and it is ignored in the studies.

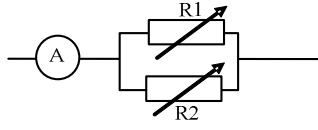


Figure 5: Resistive-type superconducting fault current limiter model

4.3 Transient studies

A three-phase to ground fault is assumed to be applied on the feeder at MV side as shown in Figure 4. The fault is applied at time $t=3.08\text{ms}$ with fault duration equal to 1s and voltage angle=0 to obtain the maximum asymmetrical current within the first half cycle. The fault duration of 1s is chosen to exceed the microgeneration fault critical clearance times that were found by the authors in [34]. The simulation studies allow the quantification of the response of the RSFCL transient model on the applied fault, and the resulting influence on the transient stability of the LV connected microgenerator.

RSFCL Response during the Fault

Figure 6 shows two results of the fault current with and without adding RSFCL at the beginning of the MV faulted feeder of the distribution network shown in Figure 4. Without adding RSFCL, the peak value of the transient fault current (peak make) has reached 22kA peak within first cycle. While with RSFCL insertion, the results have shown no pre-fault effect, but when the protected circuit is faulted, the dc component of the fault current is rapidly removed by the limiter, and the first fault current peak is reduced from 20kA to less than 5kA. The activation value to initiate the RSFCL is assumed to be equal to 3 times the full load current of the feeder, and in the simulation is equal to 600A (rms).

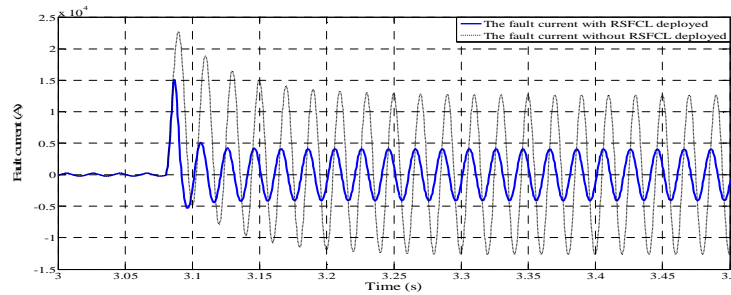


Figure 6: Fault currents with and without the inclusion of RSFCL

The results above have shown how significant the usage of the RSFCL in limiting the perspective fault current. This would lead to numbers of advantages. For example, the reduction in the fault level even if the fault current has not exceeded the allowed limit would lead to less stress including the heat that would be applied compared to not deploying RSFCL. Such application could bring significant saving in the cost particularly in urban areas. This is because lower rating equipments would be cheaper and smaller, and this in turn would require smaller spaces, and it can save some cost in the land which can be very expensive. In addition, reduction in the fault current is actually resulting in reduction in the voltage dips on the nearby areas to the fault location. Since the voltage level on the system has direct impact on the performance of the connected machines, the RSFCL influence on the transient performance of LV connected microgeneration is investigated in the next section.

Studies of LV-Connected Microgeneration Transient Stability improvement by RSFCL

The following presents the investigation of the impact of using RSFCL on the fault ride through capabilities of numbers of LV-connected microgeneration. The investigation is achieved by studying the influence of the transient characteristics of the developed limiter resistance on the transient response of the machine power and the machine slip of numbers of small microwind turbines interfaced to the grid by grid-excited single-phase induction generators, and assumed to be connected to residential level. Four microgeneration sizes are used; 1.5kVA, 1kVA (1hp), 700W, and 1.1kW. Their transient parameters are obtained from [42], [43], [44], and [45] based on different simulation and experimental tests, and they all are listed in the Appendix.

Figures 7-10 show the results of the response of different microgenerators to a remote fault on MV circuit with and without the adding the RSFCLs to MV feeders. When there no RSFCL is added, the LV circuits

has experienced a large voltage dips up to 100% drop. This has led to a high acceleration of the connected microgenerators rotors during the fault period as explained in figures 7-10. When the fault is cleared the machines have lost their transient stability, and their output powers have collapsed as shown below in figures 7-10. With the same fault condition when RSFCL is located between the main MV bus and MV feeder, the voltages of the MV bus did not fall to zero, and hence the connected microgeneration would experience retained voltage to some level. During the fault period, the machines are still capable of providing output power, so their rotors would not be accelerated to uncontrollable level. Figures 7-10 illustrate that during the fault the rotors speed were increased higher than during normal operation, but the stability is maintained. The increase in an induction generator speed means increase in the output power, but that can be true if only the speed has not exceeded its critical value. The results reflect that the machines slips are kept by the RSFCL within the stability margin until the fault is cleared. Therefore, adding RSFCL to MV feeders will remarkably limit the fault level at MV side as well as significantly improve the transient stability of downstream connected microgeneration during remote faults.

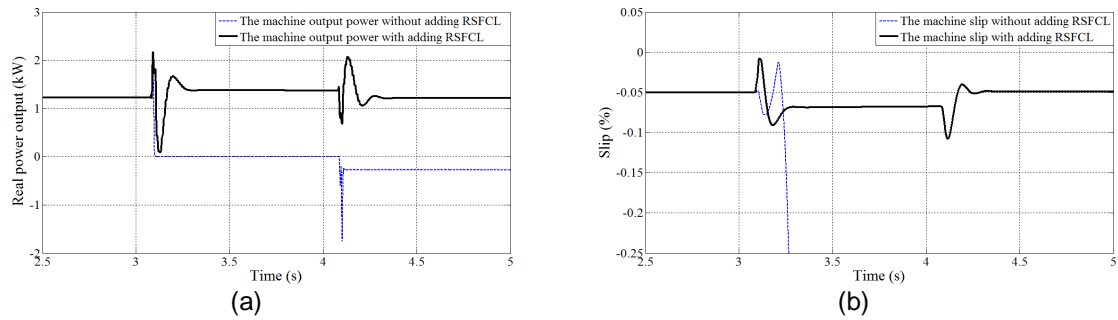


Figure 7: The transient performance of grid-excited 1.5kVA 1-phase induction generator with and without using RSFCL: (a) the real power output, & (b) the slip of the machine

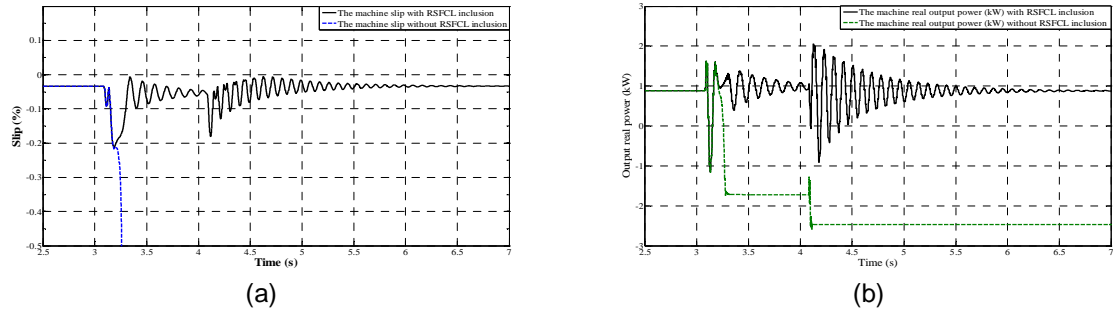


Figure 8: The transient performance of grid-excited 700W 1-phase induction generator with and without using RSFCL: (a) the real power output, & (b) the slip of the machine

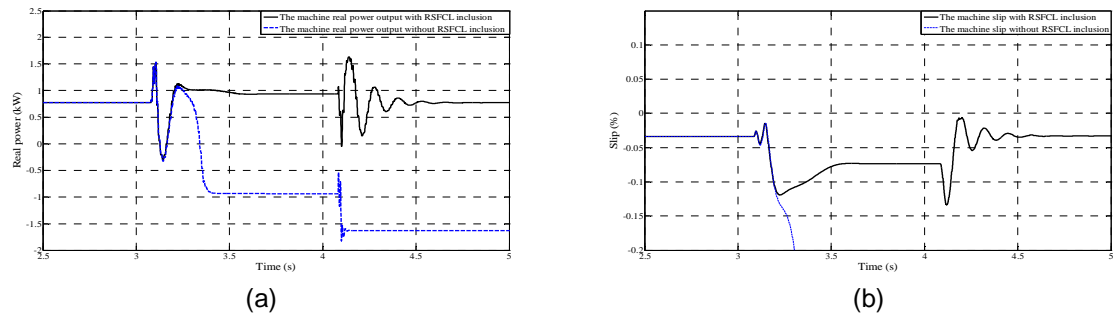


Figure 9: The transient performance of grid-excited 1kVA 1-phase induction generator with and without using RSFCL: (a) the real power output, & (b) the slip of the machine

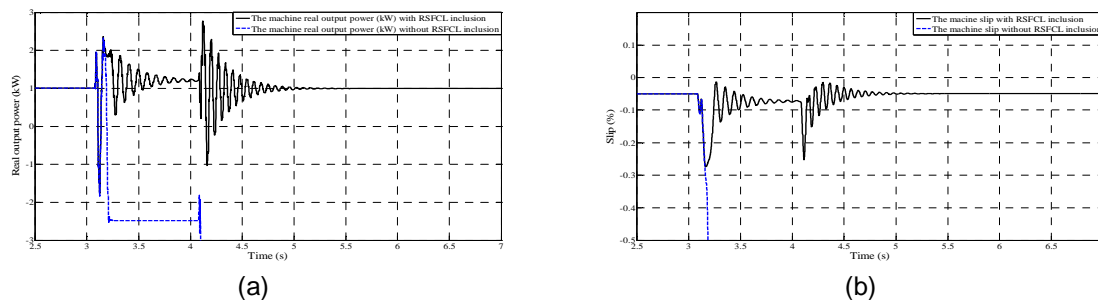


Figure 10: The transient performance of grid-excited 1.1kW 1-phase induction generator with and without using RSFCL: (a) the real power output, & (b) the slip of the machine

5- Conclusions

Increasing the volume of connected microgeneration driven by renewable and low carbon energy resources, and increased deployment of energy efficiency measures to curb GHG emissions and conserve energy resources, will change the operational structure of existing power systems. The paper proposed a cell concept as one of the solutions that can help to manage the spread of heavy volumes of distributed energy resources (DERs) including microgeneration such that benefits are maximised and the host system is supported under different operating conditions. The cell concept is based on hierarchal structures moving from one control level to another starting from individual smart devices up to higher cell levels. The benefits of a system based on the cell structure can be divided into two main facets. One is the possibility of exploiting the useful features of DER units in support of the wider system. This could help mitigate the threats to system performance presented by significant connection of passive and unpredictable DERs. The other is simpler and better coordinated communication with DERs by building the system in hierarchal structure and allowing the inputs from DERs and groups of cells to be transferred as collective actions when it moves from the consumer level to wider system level.

In order to cope with problems within a local distribution system with a high penetration of LV connected microgeneration under fault conditions, and prevent the local disturbances from expanding, the paper also proposed that MV distribution networks can be equipped by resistive-type superconducting fault current limiters (RSFCLs) by which both network fault level and microgeneration transient performance are kept within design limits. The simulation of RSFCL within the cell structure has demonstrated enhanced resilience in the face of remote disturbances. The paper has concluded that RSFCL could play an important role in ensuring that future distribution networks with microgeneration can be resilient to system disturbances.

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Biographies:



Abdullah Swissi Emhemed received the B.Eng. in Electrical Power Systems from Nasser University, Al-Khomas/Bani-waleed, Libya, in 2000, and M.Sc. degree in Electrical Power Systems from University of Bath, Bath, U.K. in 2005. He is pursuing the Ph.D. degree within the Institute for Energy and Environment at the University of Strathclyde, Glasgow, U.K. He worked for General Electrical Company of Libya (GECOL), Tripoli, Libya from 2000-2003.



Ryan M. Tumilty is a Research Fellow within the Institute for Energy and Environment at the University of Strathclyde, Glasgow, U.K. He graduated in 2004 with an M.Eng. (with distinction) in Electronic and Electrical Engineering with Business Studies from the University of Strathclyde and is currently working towards a Ph.D. His research interests include: power system modeling and simulation; protection; and network automation.



Prof. Graeme M. Burt received the B.Eng. degree in Electrical and Electronic Engineering from the University of Strathclyde, Glasgow, U.K. in 1988, and the Ph.D. degree from the University of Strathclyde in 1992, following research into fault diagnostic techniques for power networks. He is currently a professor within the Institute for Energy and Environment at the University of Strathclyde. He is currently the Director of the University Technology Centre in

Electrical Power Systems sponsored by Rolls-Royce, and is a director of the Institute for Energy & Environment. His current research interests lie in the areas of: assessing the impact of distributed generation on networks; power system modeling and simulation; power system protection and control.

Appendix:

Rating	R _{sm} (Ω)	R _{sa} (Ω)	R _{rm} (Ω)	R _{ra} (Ω)	X _{sm} (Ω)	X _{sa} (Ω)	X _{rm} (Ω)	X _{ra} (Ω)	X _{smm} (Ω)	X _{sam} (Ω)
1.5kVA	2.2	4	3.29	5	2.5	6.95	6.95	6.95	135	77
1hp	3.14	11.22	4.37	8.01	3.99	6.433	3.99	6.433	122	76.65
700W	4.0	5.0	3.4	3.4	4.5	6.95	4.5	4.5	100	90
1.1kW	2.2	7.62	3.5	1.3	3.97	2.97	0.87	0.78	32	24

Transient parameters of single-phase induction machines

R_{sm} and *R_{sa}* are the stator main and auxiliary windings resistances. *X_{sm}* and *X_{sa}* are the stator main and auxiliary windings reactances. *R_{rm}* and *R_{ra}* are the rotor winding resistance referred to the stator. *X_{rm}* and *X_{sm}* are the rotor reactances referred to the stator. *X_{smm}* and *X_{sam}* are the magnetizing reactances of the main and auxiliary windings respectively.

Abstract:

Incorporating a substantial volume of microgeneration (consumer-led rather than centrally planned) within a system that is not designed for such a paradigm could lead to conflicts in the operating strategies of the new and existing centralised generation technologies. So it becomes vital for such substantial amounts of microgeneration among other decentralised resources to be controlled in the way that the aggregated response will support the wider system. In addition, the characteristic behaviour of such populations requires to be understood under different system conditions to ascertain measures of risk and resilience. Therefore, this paper provides two main contributions: firstly, conceptual control for a system incorporating a high penetration of microgeneration and dynamic load, termed a Highly Distributed Power System (HDPS), is proposed. Secondly, a technical solution that can support enhanced transient stability in such a system is evaluated and demonstrated.