Provision of Differentiated Power Quality Using Network Based Mitigating Solutions

Citation for published version (APA):
Liao, H., Saif, J., & Milanovic, J. (2015). Provision of Differentiated Power Quality Using Network Based Mitigating Solutions. In *CIRED 2015*

Published in:
CIRED 2015

PROVISION OF DIFFERENTIATED POWER QUALITY USING NETWORK BASED MITIGATION SOLUTIONS

Huilian LIAO
University of Manchester – U.K.
huilian.liao@manchester.ac.uk

Jahangir SAIF
UK Power Networks– U.K.
jahangirsaif303@gmail.com

Jovica V. MILANOVIĆ
University of Manchester – U.K.
milanovic@manchester.ac.uk

ABSTRACT

With the increased acknowledgement of quality of supply around the world in the recent years, this paper investigates effective, network-based mitigation schemes to ensure the effective management of PQ, while considering the temporal and spatial mapping of power quality zones in distribution networks. In the study, isolated transformers, phase shifting transformers, undergrounding techniques and series reactors are investigated to mitigate PQ phenomena on a 295-bus generic distribution network. The mitigation effect of these techniques is presented statistically at system level and at zonal level. The results have shown that the variation of system level and zonal PQ performance is pronounced when different mitigation techniques are applied. Differentiated PQ performance can be provided by selecting appropriate mitigation techniques and proper zones to implement these mitigation techniques.

INTRODUCTION

A paradigm shift on acknowledgement of Power Quality (PQ) by utilities, end users and regulatory bodies around the world is evident in the recent years. From utilities' perceptive quality of supply can be defined as reliability of the system. PQ issues are attributed to sensitive equipment, new regulations, standards regarding PQ and ever increasing competition in electricity market. Besides, the increased penetration of non-conventional electricity generators, i.e., distributed generators (DG), raises a lot of operational challenges regarding PQ phenomena. Various types of DG have different impacts on quality of supply, for example wind generators and intermittent photovoltaic can lead to voltage fluctuations. Power electronics used as connection interface will lead to PQ disturbance, e.g., increase in harmonic level in the network. Due to the frequent interruption to equipment/processes, PQ issues result in substantial financial losses to customers and utilities [1-4]. This has raised increased awareness of PQ by the customers and utilities. Thus it is very important to meet required PQ standards all the time to avoid significant economic losses for both network operators and customers.

Due to diverse requirements of different customers to PQ level, there is a necessity to provide differentiated PQ based on customer classification. Customers can be categorized based on their requirements to PQ performance and the effect of PQ disturbances on their activities, using a general scheme known as electro-economic nature of methodology [5]. This methodology is developed by arranging customers based on their sensitivity to PQ disturbances while considering the economic losses due to unexpected PQ events. With this approach, PQ requirements in different areas/zones of the network can be determined.

One of the main tasks for system operators is to provide optimum provision of PQ to ensure the cost proficiency of the solution and hence charge the customers accordingly. This is a complex issue for system operators as end users may have different requirements in various geographical zones. Most of the customers are not willing to pay extra money to improve PQ, then it not optimal for system operators to improve the overall quality of supply for the whole network. Hence the ideal solution is to address the problem locally/zonally. In practical, premier contracts have been developed to address various requirements of the customers and their willingness to pay for better quality of supply [6]. DNOs like EDF in France and Detroit Edison Company in USA have introduced contracts similar to premier contracts since the mid-nineties. Different from premier contracts, provision of differentiated PQ considers various PQ requirements across the network, rather than considering only the premier areas. In this case, all customers' requirements are accounted for in mitigation planning process.

In order to ensure that the level of PQ phenomena remains at the desired level as per the target set by the regulator, optimal mitigation schemes must be applied to pro-actively meet the zonal customer requirements while considering different aspects of the realistic network and to comply with PQ regulations. PQ mitigation can be handled at various levels, for example at equipment level, process level, plant level and network level. Mitigation at process and equipment levels only provides limited immunity to financial loss due to inadequate PQ; hence immunity outside their tolerance limits has to be dealt at a higher level. Using the mitigation approaches at plant level and network level can ensure better immunity. Mitigation at plant level uses real time compensation monitoring for PQ events using power devices and harmonics filters. Commonly used devices for voltage sag are dynamic voltage restorers (DVR), static VAR compensator (SVC), distribution static compensator (DSTATCOM) and uninterruptible power supplies (UPS) [7-9]. Voltage source converter (VSC) based shunt active filter are commonly used as mitigation devices for harmonics compensation of line current. Despite their efficiency in voltage sag mitigation, their application is still somewhat limited due to their high cost [10]. Alternatively, network level approaches use general principle that is prevention is better than cure. Instead of buying any expensive devices like Flexible AC Transmission (FACT) devices to mitigate PQ issues, network based mitigation uses existing network resources effectively to resolve quality of supply issues. In this case, wide scopes of applications are used for PQ mitigation and overall benefits are achieved when performed at network level. It includes solutions like tree trimming schedule, replacing overhead lines with cables and installing surge arresters to resolve sag issues. Similarly for harmonic distortion, network based mitigation techniques include the use of in-line reactors, isolation transformers, phase shifting transformers, k-factor transformers and 18 pulse rectifiers.

In this paper, a number of network-based mitigation techniques are investigated to mitigate PQ phenomena (e.g., voltage sags and harmonics). The PQ evaluation procedure and effect of the mitigation techniques are illustrated on a 295-bus generic distribution network. The variation of operation conditions with respect to load demand and DG outputs is considered in the study. The simulation results are statistically presented at system level and zonal level. The results show that differentiated PQ performance can be achieved by selecting appropriate mitigation schemes and the locations for implementing these mitigation techniques.

FRAMEWORK - MITIGATION PLANNING

PQ issues include a wide range of various phenomena. For each PQ phenomenon there is a different cause and different mitigation schemes that can be used to improve the performance of the equipment and the quality of supply of the system as a whole. The general framework for power quality investigation can be defined as five steps, as illustrated in Fig. 1. The first step is to recognise the problem category, which means to identify which PQ phenomena need to be mitigated. The second step is problem characterisation. In this step the selection of right index plays pivotal role as different indices represent different concerns and perspectives. The next step is to recognise different mitigation schemes available to attain standard quality of supply in different zones of the network. Mitigation schemes obtained from the third step need to be evaluated considering the system as a whole while taking into the account both technical limitations and economics for the network, i.e., the fourth step. The solutions that are not technically viable are discarded and the rest of the solutions are evaluated on economics basis. The fifth step is the process of decision-making about the optimal solution. In this paper, the PQ analysis follows this general framework. Two important PQ phenomena, voltage sags and harmonic, are considered here. The statistical results representing the mitigation effect of each potential mitigation solution are then compared with standard compatibility levels or zonal requirements if they are available, in order to make the final decision on the optimum mitigation schemes.

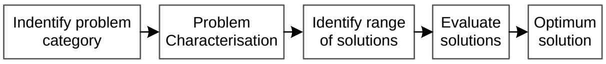

Fig. 1. General procedure in PQ evaluation (adopted from [11]).

Harmonics

Problem Characterisation

There are various indices to analyse the performance of harmonic distortion, but the most common one is Total Harmonic Distortion (THD). THD is recommended in EN 50160 and is widely used to evaluate the harmonic distortion globally [12]. It evaluates the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{1}$$

Identify Range of Network-based Solutions

There are various network based mitigation schemes for harmonic phenomena [13], such as line reactors, isolation transformers, shunt capacitor banks, K-factor transformers and phase shifting transformers. The shunt capacitor banks can be used to modify an unfavourable system response to bring the harmonic distortion to an acceptable level. Using line reactors is one of the simplest and cheapest mitigation techniques for harmonic phenomena. Apart from that, using isolation transformers is another way in which PQ phenomena like harmonics can be eliminated. Isolation transformers are used to effectively reduce harmonic distortion using input circuit reactance which is one of the major factors in determining the magnitude of harmonics that will be present and flowing to an individual load. The leakage inductance of isolation transformer offers suitable values of circuit impedance to ensure that harmonics are attenuated. The K-factor transformer is designed to control rise in temperature due to current harmonics in the transformer windings and fundamental frequency losses. K-factor is a constant that specifies the ability of the transformer to control harmonic heating. In order to implement harmonic distortion schemes, phase shifting transformers (quasi 12-pulse methods) have been used to attenuate harmonics. In this method two phase shifted transformer windings are connected to two sets of non-linear loads. It can be implemented using a single transformer which has two separate windings (i.e., delta and wye) or using two separate transformers with one configured as delta primary / wye secondary and the other configured as delta primary / delta secondary. Phase shifting transformers help to cancel 5th and 7th harmonics on the primary side of the transformer to the extent that these currents are balanced in each of the secondary windings of the transformer.

Voltage sags

Problem Characterisation

Voltage sags are regarded as the most harmful PQ disturbance due to the costly impact on industrial processes. In the study, sag performance is characterized using Bus Performance Index (BPI) [14, 15],

$$\mathrm{SSI}_{\mathrm{B}ij}^{\mathrm{C}_w} = \left(\sum_{x=1}^{y-1} ax \times \frac{\mathrm{V}_{\max}(\mathrm{T}_x)-v_{\mathrm{B}ij}}{\mathrm{V}_{\max}(\mathrm{T}_x)-\mathrm{V}_{\min}(\mathrm{T}_x)}\right) + ay \times \frac{\mathrm{V}_{\max}(\mathrm{T}_y)-v_{\mathrm{B}ij}}{\mathrm{V}_{\max}(\mathrm{T}_y)-\mathrm{V}_{\min}(\mathrm{T}_y)} \times \left(\frac{t_{\mathrm{B}ij}-\mathrm{T}_{\min}(\mathrm{T}_y)}{\mathrm{T}_{\max}(\mathrm{T}_y)-\mathrm{T}_{\min}(\mathrm{T}_y)}\right)^{b^{y-1}} \quad (2)$$

$$\mathrm{BPI}_{\mathrm{B}ij}^{\mathrm{S}} = \sum_{j=1}^{4MN} f_{\mathrm{B}ij} \times \mathrm{SSI}_{\mathrm{B}ij}^{\mathrm{M}} \quad (3)$$

where C_w refers to the sag tolerance curve used for assessment, variables x and y denote the severity ranges the sags locate in, and $\mathrm{B}ij$ denotes the j^{th} sags occurring at bus *i*. This index evaluates the level of voltage sag performance from the perspective of utilities and customers in distribution networks. The index takes into account various sag characteristics simultaneously as well as the sensitivity of equipment to voltage sags. It accounts for sag magnitude, sag duration, sag occurrence frequency, the sensitivity of equipment to voltage sags, the uncertainty of voltage tolerance curve, the stochastic nature of load variation and the uncertainty of sag characteristics. It reflects to a good approximation the practical consequence of voltage sags from the point of view of system/equipment operation. With this index, voltage sag performance across the network can be assessed, and customer requirements can be evaluated.

Identify Range of Network-based Solutions

For voltage sags the main concern is to avoid the tripping of sensitive equipment. Voltage sags observed in distribution networks are mainly caused by short circuit faults in the transmission and distribution networks, starting induction motors and switching large loads. The number of faults can be reduced by implementing network based mitigation for sags. The most typical causes for faults can be categorized into short circuit for bare wires, lightning induced faults, faults due to equipment failure and accidental faults on underground cables due to dig-ins work, etc. Frequent tree trimming schedules by DNOs will help to avoid any contact due to falling tree branches, covering overhead lines with the insulation and replacing overhead lines with cables also help to reduce faults in the network. Likewise the lightning faults can be reduced by installing shield wires and surge arresters, converting overhead lines with cables and insulating lines. Apart from that contact faults due to animals and wind can be minimized by installing animal guards, insulating lines and converting overhead lines to cables. Better communication and data recording systems will help to reduce the accidental dig-ins due to construction work. Proper data storage of cable locations and availability of information prior to constructional work will help to avoid faults due to accidental dig-ins work. The mitigation of voltage sags can also be achieved through network reconfiguration. The use of fault current limiters to alter system impedances during a fault has also been proven successful in reducing sag propagation. Placement of fault current limiters at strategic locations around the network can reduce the severity of sags at the selected busbars. The conventional way of fault current limiting is achieved by placing line reactors at feeders around the network.

SIMULATION RESULTS - PQ EVALUATION

Once the range of potential mitigation solutions is identified, their mitigation effect can be evaluated based on the selected indices mentioned above. The procedure of PQ evaluation is illustrated on a large scale distribution network (295-bus Generic network), as shown in Fig. 2. The network is divided into three zones circled by solid red lines. All simulations related to voltage sags and harmonics are implemented in commercially available DIgSILENT/PowerFactory, and statistical results are processed in MATLAB tool. In the study, three different operating points (OPs) are used. These OPs are corresponding to the maximum cluster, the maximum load and the maximum DG respectively. The maximum cluster is obtained using K-mean approach to find the most possible operating condition which is present most of the time in the year. This OP is considered as the normal operating condition. The maximum load represents the point when load demand is the maximum while considering the time span of whole year. The maximum DG is for the point when the output of the total DGs is the maximum. In this study three different types of DG, i.e., fuel cell, wind and photo-voltaic, are considered.

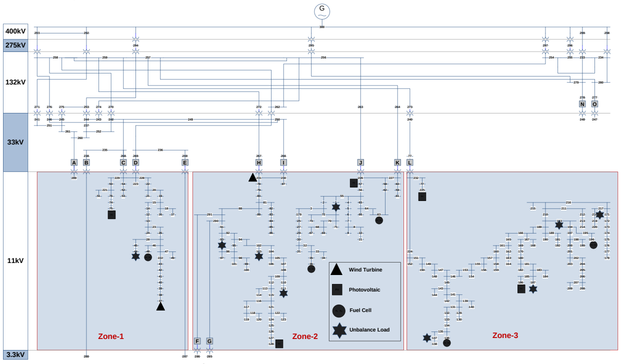

Fig. 2. Illustration of 295-bus generic distribution network and its divided three zones.

Harmonic mitigation

Using isolated transformers

In this test network there are 10 fixed non-linear loads and 20 non-linear loads which are randomly selected across the network. The 10 fixed non-linear loads are selected to implement isolated transformer techniques. There are 2 fixed non-linear loads in zone 1, 5 in zone 2 and 3 in zone 3. Five study cases are evaluated in the study, and their settings are given in Table 1. The results with and without mitigation techniques (isolated transformers) are given in Table 2. Through the comparison among the three operational conditions (the maximum cluster, the maximum load and the maximum DG), it can be seen that the increase in load demand has larger impact on the harmonic performance, compared to the increase in DG outputs. In Table 2, for each operational condition the best zonal performance and the best network level performance among the five study cases are highlighted in bold. It can be seen that the variation of network level performance (and zonal level performance) in different study cases is pronounced. It is important to select the appropriate mitigation solutions to improve the performance of the whole network while at the same time considering zonal requirements. For instance, in the case of the maximum load, case 5 can be selected to obtain the best network level performance. However, if zonal performance is the main concern, the comparison should be based on the received harmonic results of each zone and the zonal requirements set based on customers. It can be seen that in the case of the maximum load, zone 1 receives the best harmonic performance in case 3, while zones 2 and 3 have the best harmonic performance in cases 5 and 1 respectively. To provide differentiated PQ that meets the provided zonal requirements, the zonal harmonic performance should be considered in decision-making of the optimum solution.

Table 1 Settings of placing isolated transformers

cases	Mitigation techniques are applied to
Case 1	None
Case 2	The fixed non-linear loads in all three zones
Case 3	The fixed non-linear loads in zones 2 and 3 only
Case 4	The fixed non-linear loads in zones 1 and 2 only
Case 5	The fixed non-linear loads in zones 1 and 3 only

Table 2 THD obtained from the three OPs respectively using isolated transformers

CASES	**MAXIMUM CLUSTER**			
	ZONE1	**ZONE2**	**ZONE3**	**NETWORK**
CASE 1	1.1242	0.3570	**1.4854**	0.957246
CASE 2	1.0091	0.8032	1.5152	1.132577
CASE 3	1.4538	0.9919	1.8292	1.418230
CASE 4	0.8813	2.1417	1.8441	1.795630
CASE 5	**0.5395**	**0.1977**	1.5261	**0.804677**
	MAXIMUM LOAD			
	ZONE1	**ZONE2**	**ZONE3**	**NETWORK**
CASE 1	3.3096	1.8816	**3.0614**	2.62026
CASE 2	4.0716	3.5599	12.649	7.38889
CASE 3	**2.9248**	1.1570	10.143	5.16639
CASE 4	5.1027	3.1238	6.1763	4.73039
CASE 5	3.8826	**0.6309**	3.5079	**2.39127**
	MAXIMUM DG			
	ZONE1	**ZONE2**	**ZONE3**	**NETWORK**
CASE 1	1.0132	0.3175	3.0377	1.55972
CASE 2	**0.4120**	**0.2028**	**2.2059**	**1.06374**
CASE 3	1.3169	1.7757	4.0788	2.64144
CASE 4	1.1345	0.4560	2.6749	1.48655
CASE 5	0.5652	0.2891	2.7241	1.33952

In the study, it is assumed that the three operating conditions are equally important to the final decision. In this case, the average of the THDs obtained from the three OPs is calculated to represent the harmonic performance. Table 3 provides the average THD index, and it shows that in case 5, both zones 1 and 2 achieve their best harmonic performance. These results can be compared with zonal requirements if differentiated PQ requirements are imposed.

Table 3 Averages of THDs obtained from the three OPs using isolated transformers

	AVERAGE THD Index VALUE For			
	ZONE1	ZONE2	ZONE3	NETWORK
CASE 1	1.82	0.85	**2.53**	1.71
CASE 2	1.83	1.52	5.46	3.20
CASE 3	1.90	1.31	5.35	3.08
CASE 4	2.37	1.91	3.57	2.67
CASE 5	**1.66**	**0.37**	2.59	**1.51**

Using phase shifting of transformers

In order to implement phase shifting of transformers, the winding of transformers connected at distribution level in zones 1 and 3 is considered. For zone 1, two transformers (Tx21, Tx20) are connected at distribution level and zone 3 has one transformer (Tx17) that is connected at the distribution level and by default all the transformers have phase shift of 30 degrees. To consider various cases to analyse the harmonic performance, three possible transformer windings are considered. They are delta primary and wye secondary (DY), wye primary and delta secondary (YD), and delta primary and delta secondary (DD) or delta primary and wye neutral secondary (DYN). In order to find the best combination of transformer windings, eight different cases are considered, as shown in Table 4. These eight cases are to cover the wide range possibilities of winding combinations. The average value of THDs at network level and zonal level is provided in Table 5. It can be seen that the winding combination as given in case 1 provides the best system level harmonic performance. As for zonal performance, zones 1, 2 and 3 receive their best harmonic performance in cases 2, 5 and 1 respectively.

Comparing between Tables 3 and 5, it can be seen that using isolated transformers can obtain better harmonic performance compared with the case of using phase shifting of transformers.

Table 4 Settings of applying phase shifting of transformers

	Combination of phase winding		
	Zone 1		Zone 3
transformers	Tx21	Tx20	Tx17
Case 1	D YN	D YN	D YN
Case 2	D Y	D Y	D YN
Case 3	D Y	D Y	D Y
Case 4	Y D	Y D	D YN
Case 5	Y D	Y D	Y D
Case 6	D D	D D	D YN
Case 7	D D	D YN	D YN
Case 8	D D	D D	D D

Table 5 Averages of THDs obtained from the three OPs using phase shift of transformers

	AVERAGE THD Index VALUE For			
	ZONE1	ZONE2	ZONE3	NETWORK
CASE 1	1.82	0.85	**2.53**	**1.71**
CASE 2	**1.37**	2.90	2.93	2.64
CASE 3	2.01	0.85	2.67	1.81
CASE 4	2.12	1.69	3.97	2.71
CASE 5	1.44	**0.55**	5.01	2.54
CASE 6	3.34	2.39	3.60	3.06
CASE 7	1.60	1.02	3.50	2.14
CASE 8	2.39	1.85	3.79	2.74

Sag mitigation

Using undergrounding

Voltage sags in distribution networks are mainly caused by short circuit faults. Replacing overhead lines with cables is known as undergrounding. It is one of the processes used to mitigate sags in the network. In the test network, there are 276 lines including overhead lines and cables. In order to analyse the impact of replacing overhead lines with cables five overhead lines are changed to cables to see their impact on BPI value. Two overhead lines in zone 2 are replaced with cables and three overhead lines in zone 3 are replaced with cables. These overhead lines are chosen in a way that they are the most critical overhead lines in the network. Then the results obtained with and without mitigation schemes are compared. The average BPI values obtained from the three OPs are given in Table 6. It can be seen that both zonal performance and network level performance are improved with the use of undergrounding techniques.

Table 6 Averages of BPIs obtained from the three OPs using undergrounding technique

	AVERAGE BPI Index VALUE For			
Mitigation	ZONE1	ZONE2	ZONE3	NETWORK
Without	0.52	0.55	1.80	1.06
With	**0.49**	**0.53**	**1.75**	**1.03**

Using series reactors

Current limiting methods mitigate sag issues using series reactors. A conservative reactance value of 0.1 (p.u.) is adopted in the study. Four study cases, with respect to various numbers of placed reactors, are analysed in the study, as given in Table 7. The average of the BPIs obtained from the three OPs is provided in Table 8. It can be seen that case 4 provides the best results with respect to zonal and network level performance. Compared between Tables 6 and 8, it can be seen that using series reactors can produce better results than using undergrounding techniques.

Table 7 Settings of placing series reactors

cases	settings
Case 1	without mitigation
Case 2	Place one series reactor in each zone for the bus which gives highest BPI index value in each zone.
Case 3	Place three series reactor in each zone for the bus which gives the highest BPI index value in each zone.
Case 4	Place six series reactor in each zone for the bus which gives highest BPI index value in each zone.

Table 8 Averages of BPIs for using series reactors

	AVERAGE BPI Index VALUE For			
	ZONE1	ZONE2	ZONE3	NETWORK
CASE 1	0.52	0.55	1.80	1.06
CASE 2	0.52	0.54	1.77	1.04
CASE 3	0.52	0.54	1.77	1.04
CASE 4	**0.48**	**0.53**	**1.75**	**1.02**

CONCLUSION

This paper investigates network based mitigation schemes to provide differentiated PQ across the network. The PQ evaluation procedure and mitigation schemes are illustrated on a 295 distribution network which has three PQ zones. For harmonic phenomena, the techniques of isolated transformers and phase shifting of transformers are evaluated. To cover the possible settings with respect to the zonal locations selected for applying mitigation techniques, five and eight study cases are considered for the two aforementioned techniques respectively. The statistical results show that variation of network level performance (and zonal performance) in different study cases is pronounced. In general, using isolated transformers can obtain better harmonic performance than using phase shifting of transformers, with respect to zonal performance and network level performance. Differentiated PQ performance can be achieved by selecting appropriate zones to implement the mitigation schemes. For sag phenomena, the techniques of using undergrounding and series reactors are investigated. The results show that using series reactors can produce better results than using undergrounding techniques.

REFERENCES

[1] J. Y. Chan, J. V. Milanović, and A. Delahunty, "Risk-based assessment of financial losses due to voltage sag," *IEEE Trans. Power Del.*, vol. 26, pp. 492-500, 2011.

[2] "GRID 2030: A national vision for electricity's second 100 years," United States Department of Energy Office of Electric Transmission and Distribution, 2003.

[3] "5th CEER Benchmarking Report on the Quality of Electricity Supply," Council of European Energy Regulators, CEER, Brussels,2011.

[4] J. G. Lglesias *etc.*, "Economic framework for power quality, JWG CIGRE-CIRED C4.107," 2011.

[5] J. Thomas, "Development of methodology for online provision of differentiated quality of electricity supply," MSc. Electrical Power Systems, Fac. of Eng. and Phys. Sciences, The University of Manchester, 2012.

[6] E. L. M. Smeets, W. T. J. Hulshorst, and J. A. Wolse, "Premium Power Quality contracts and labeling," KEMA 2007.

[7] R. Grunbaum, "FACTS for voltage control and power quality improvement in distribution grids," in *Proc. CIRED Seminar Smart Grids for Distribution*, 2008, pp. 1-4.

[8] H. Hatami, F. Shahnia, A. Pashaei, and S. H. Hosseini, "Investigation on D-STATCOM and DVR Operation for Voltage Control in Distribution Networks with a New Control Strategy," in *Proc. IEEE Lausanne Power Tech*, 2007, pp. 2207-2212.

[9] J. V. Milanović and Y. Zhang, "Modeling of FACTS devices for voltage sag mitigation studies in large power systems," *IEEE Trans. Power Del.*, vol. 25, pp. 3044-3052, 2010.

[10] A. Baggini and F. Bua, *Costs: Investment analysis for PQ solutions*: Leonardo Power Quality Initiative, 2004.

[11] R. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality (2 Ed.)*. New York: McGraw-Hill, 2002.

[12] EN 50160:2004, "Voltage disturbances standard EN 50160 - voltage characteristics in public distribution systems," ed, 2004.

[13] G. Sandoval and J. Houdek, "A Review of Harmonic Mitigation Techniques," 2005.

[14] H. L. Liao, S. Abdelrahman, Y. Guo, and J. V. Milanović, "Identification of weak areas of power network based on exposure to voltage sags—Part II: assessment of network performance using sag severity index," *IEEE Trans Power Del. (accepted)*, 2014.

[15] H. L. Liao, S. Abdelrahman, and J. V. Milanović, "Identification of weak areas of power network based on exposure to voltage sags — part I: development of sag severity index for single-event characterization," *IEEE Trans Power Del. (accepted)*, 2014.