2018

# The Potential for Power Quality Problem Mitigation Through STATCOM

Arsalan Zaidi
*Technological University Dublin*

Keith Sunderland
*Technological University Dublin*, keith.sunderland@tudublin.ie

Michael Conlon
*Technological University Dublin*, michael.conlon@tudublin.ie



## Recommended Citation

Zaida, A.H., Sunderland, K. & Conlon, M. (2018). The Potential for Power Quality Problem Mitigation through STATCOM. *20th European Conference on Power Electronics and Applications, EPE 2018 ECCE Europe; Riga; Latvia; 17 September 2018 through 21 September.*

# The potential for power quality problem mitigation through STATCOM (BESS-STATCOM)

Arsalan Hussain Zaidi, Keith Sunderland, Michael Conlon
Dublin Institute of Technology, DIT
Kevin Street, Dublin 8
Dublin, Ireland
email: arsalan.zaidi@mydit.ie

## Keywords

«Static Synchronous Compensator (STATCOM)», «Electric vehicle», « Smart grids», « Distribution FACTS (DFACTS) », «Distributed Generation»

## Abstract

Consideration of spatial and temporal diversity of EV charging demand has been demonstrated to reduce the estimating impacts on the distribution networks. The data formulation is based on impact studies of Electrical vehicles (EVs) on distribution networks. It is suggested that Distribution System Operator (DSO) could benefit for new innovation/advancement in the market (BESS-STATCOM) in a way that makes networks more reliable/robust, In this regard such innovation creates more opportunities for demand side management, reduces planning uncertainties associated with stochastic nature of EV charging and makes space for demand side management.

This work considers probabilistic load flow in a representative unbalanced distribution network and through Monte Carlo simulation increased the hosting capacity for DG/EV is considered in an Irish/UK context. Furthermore, this paper considers the potential for a distribution network deployed STATCOM in supporting EV penetration, while maintaining appropriate power quality (voltage) standards. To reduce the computation burden of Monte Carlo simulation an alternative (novel but simple) method is applied. In terms of the Irish/UK DSO perspective, this work will help to increase the hosting capacity of DG/EV without breaching power quality limits.

## Introduction

Over the last decade, cities are becoming engaged in strategic energy developments; availing of indigenous opportunities to contribute towards achieving energy policy goals. Cities consume more than 65% of the world's energy requirements and produce more than 60% of the total greenhouse gas emissions [1], a significant portion of which are derived from transportation sector. Over the last decade, cities are becoming engaged in strategic energy developments; availing of indigenous opportunities to contribute towards achieving energy policy goals. Electric vehicles (EVs) are being viewed as a potentially effective technological response to address road transport emission targets [2]. Many cities are considering policies to actively increase the number of EVs on their roads and ban diesel cars altogether by 2025 as a means to tackle air pollution [3]. Examples include Paris, Mexico City and Athens. However, the potential for EVs to reduce greenhouse gas emissions depends on the nature of electricity generation used to charge EV batteries. Electric transportation, including Electric Buses (EBs) and Electric Vehicles (EVs), are examples of important measures for greenhouse gas reduction and as such avail of subsidy measures to enhance willingness to use EBs and purchase EVs [2, 4]. So along with the potential for the mass penetration of new technologies, such as electrical vehicles and micro-generation, the power quality associated with distribution networks is likely to be affected. However, the smart control of distribution generation, demand response services and electric vehicles is also essential. Promoting EV use in urban environments has practical implications around electric grid capacity for mass EV charging, as the increased capacity required by a mass uptake of EV's will require significant infrastructure investment to upgrade the existing grid supply

Fig. 1 illustrates a basic concept to explain how Electrical vehicle and DGs could impact the distribution network [5]. So if they are connected to grid for 15-18 hours, even with a particular driving/travelling distance/period, there will be (in the context of a charged battery) opportunity to support the grid against the inevitable fluctuations prevalent as a consequence of EV and renewable DG integration. Travelling requirements of passenger cars are considered in order to design more realistic EV battery load profiles. In general slow charging (3kW) can take approximately eight hours to fully replenish the EV battery from a discharged state. Fast charging (7-22kW) will take around three to four hours to fully replenish an EV battery from zero charge [6]. In general, an EV battery may require 3.68 kW to charge (0% to 100%) completely for eight hours but travelling patterns suggest passenger cars only consume 25% of total battery charge in a day [6]. So in this regard, the associated batteries do not need to charge every day from 0%-100%. So, in that case, 25% EV battery consumption requires 3.68 kW for two hours not for eight hour to charge completely. In this respect, the state of charge (SOC) of the battery is 75% (25% battery consumed, implies 75% is still available). The SOC of EVs is the required metric to appreciate the energy available in the battery.

In Fig. 1, DGs have uncontrolled generation and EVs have uncontrolled load, but can be controlled through charging pattern manipulated (Smart charging). The distribution network, during off-peak times may have excess power/energy available. This energy could potentially be stored in batteries so that they in turn can act as a battery energy storage system (BESS) to buffer network (voltage) fluctuations. Once connected to the grid, this BESS could provide support to the grid in peak-load hours. Excess active power from such a battery system can be controlled through proper controlling techniques based on battery storage and embedded along with STATCOM (i.e. in the context of reactive power support), so that LV network could employ both active and reactive power compensation when required. The integration of DG and EV into a distribution network requires comprehensive planning studies to evaluate the possible voltage instability. The instability issues caused by the contributions of DGs/EVs require voltage magnitude investigation throughout the network. This paper will also investigate whether STATCOM can provide viable mitigation opportunities (see Fig. 1 below).

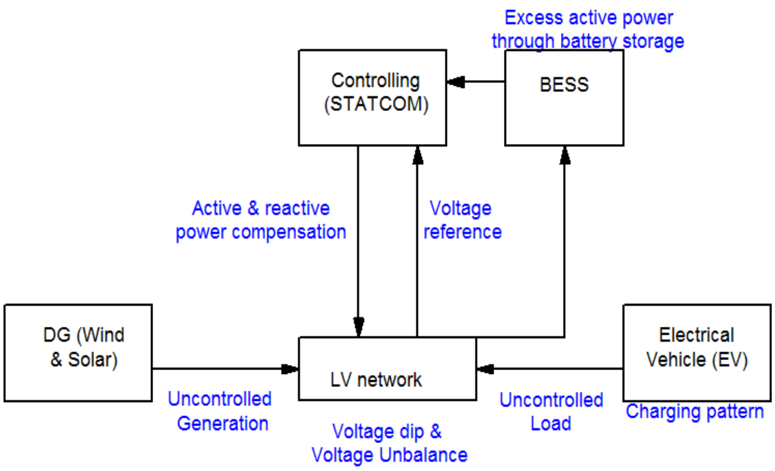


Fig. 1: Simplified illustration of DG/EV and controlling technique

It is becoming increasingly apparent that more EVs/DGs are being integrated into the distribution network and this trend is expected to continue in the near term. Random placement of DGs/EVs can cause significant amount of power quality issues in the network. Considering the probabilistic characteristics of DGs/EVs can allow a better understanding of the problem. An electrical power system is always subject to the various types of uncertainties like generation variation, load variation and faults. The effect of these uncertainties can be exacerbated by the integration of DG/EV in the network.

Power flow studies are used to investigate the power system in terms of magnitude and angle of voltage at busbars. Load flow studies are solely deterministic in nature. Although power flow provides useful information about load and generation, time variant (dynamic) uncertainties are not considered.

Power flow analysis is therefore unable to define uncertainties associated with renewable energy sources accurately so as a result, the power flow analysis cannot directly influence the decision making for distribution systems operators (DSO). Probabilistic aspects of these uncertainties can provide better understanding of the input load/generation variation. These uncertainties can be integrated through probability theory such as Monte Carlo Simulation (MCS) technique. The Monte Carlo Simulation technique is quite accurate but requires high computation burden. Probabilistic aspects of load/generation embedded in the power flow studies is known as 'Probabilistic load flow (PLF)'. Input/output parameter variations are added as random variables based on associated probability of occurrence. The results are obtained in terms of a possible range of voltage levels and currents (loadings) of the line.

Based on the literature, PLF analysis can be divided into three main categories: Monte Carlo simulation (MCS) based method [7], analytical methods [8, 9] and estimation/approximation methods [10]. Monte Carlo simulation (MCS) is widely used for planning purposes as it does not involve any sort of approximation during the solving of the power flow problem. MCS method is based on the repetitive iteration of random input variable until solution convergence is achieved. The simulation computation time and storage are the main pitfalls of this method.

This paper discusses the role of battery energy storage systems (BESS) in mitigating the intermittency caused by DG/EV along with modelling the uncertainty through (spatial) probabilistic load flow (PLF) that is based on Monte Carlo simulation and temporal analysis. In a UK/Irish prospective, the DSO is increasingly considering accommodating new trends in distribution networks. Households are supplied as single phase connections. To change every household load from single phase to three phase connections would require a substantial infrastructure change. The work presented here is based on the impact of a higher EV charging rate on single phase connected distribution network and the ability of a STATCOM to mitigate the voltage magnitude issue(s). Embedding a BESS with a STATCOM can provide active and reactive power support in order to mitigate frequency and voltage variation respectively.

# Analysis

In general terms, the methodology consists of two main sections.

- Spatial Analysis (probabilistic load flow is calculated based on Monte Carlo Simulation).
- Temporal Analysis (Dynamic modelling of BESS-STATCOM)

## Network Modelling

The network model is implemented on the DIgSILENT power factory platform. There are 74 customers, connected from a 10/0.4 kV transformer in a radial network topology. In this regard the LV distribution network considered in [11], as provided in Fig. 2 below, is employed. It is worth mentioning that a 11kW (single-phase) connected EV load is in excess guideline published by ESB. Under current regulations, 20% EV load penetration is allowed with charging rate of 3.68 kW. The considered BESS-STATCOM capacity is selected on the basis of active power available. In this regard, 380 kW is available through BESS, with reactive power of 120 kVAr, which implies a power factor of 0.95. The BESS-STATCOM capacity available for active and reactive power, is 400 kVA.

As defined in the EN50160 standard [12], the voltage at every bus of the medium and low voltage networks should be within ±10% of its nominal value, with ±6% being employed by the network designers. The network generation connection strategy illustrated in [13] is used. In this regard therefore, the load/generation pertaining to the day being considered is employed with the generator profiles. For the DpvG, the Skoplaki methodology [14] was employed and for load profiles, the Commission for Regulation of Utilities[1] (CRU) [15] load data was utilised. In terms of the generation, local meteorology measurements from an urban site in Dublin, Ireland were employed.

[1] Formerly the Commission of Energy Regulation (CER)

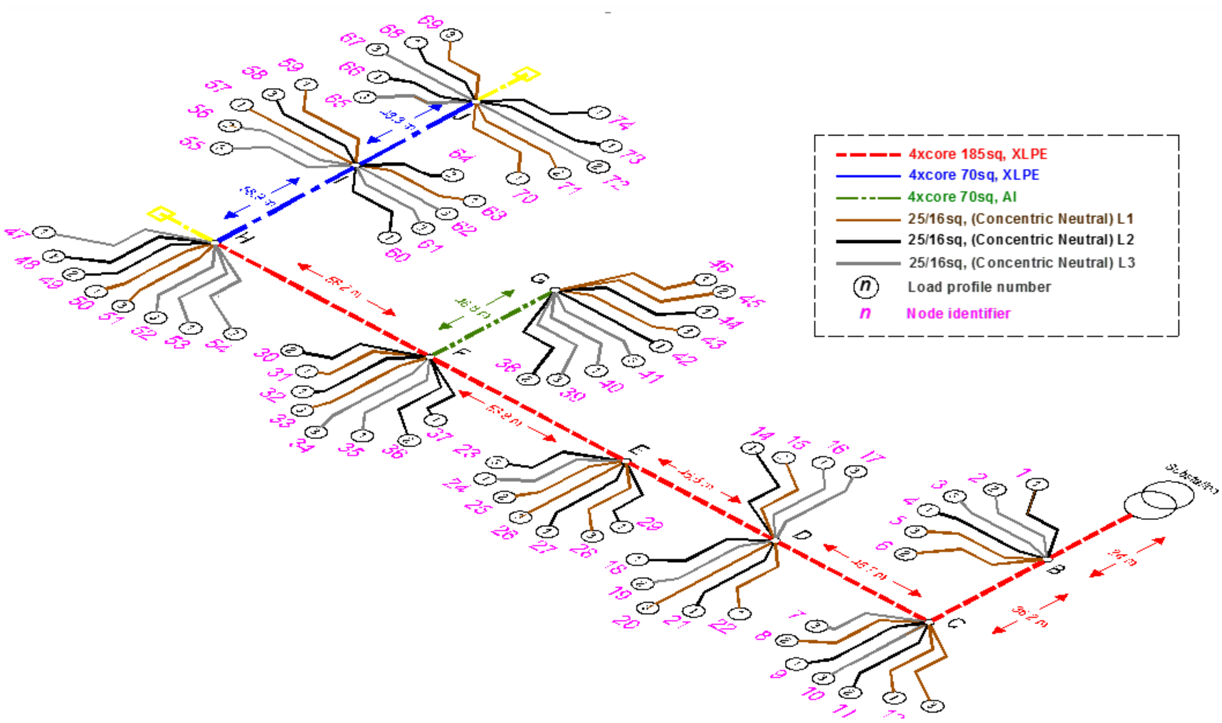


Fig. 2: Section of Irish distribution network *[11]*

## Spatial Analysis (Extent of voltage problem)

Firstly, PLF is implemented based on algebraic equation and MCS simulations are calculated through DPL (DIgSILENT programming Language) script implementation in DIgSILENT power factory. Then for temporal analysis, DSL (DIgSILENT simulation language) to monitor the dynamic behaviour of the BESS-STATCOM.

### Probabilistic Impact Assessment

The probabilistic impact assessment methodology described herein is cognisant of the uncertainties related to EVs. The probability density function implemented in this work is reflective of size, location and charging of the EV batteries via Monte Carlo Simulations (MCS). 100 different sets of data are prepared from each EV load and during MCS, EV loads are randomly selected from these datasets. It is worth mentioning that normally, 10,000 iteration are considered to avoid pre-mature convergences but literature suggests 100 iteration can provide reasonable accurate results [16] Different penetration levels are selected from 30% to 100%, in 30% step sizes. Different penetration levels selected, based on percentage of EV penetration level, are investigated through a sequence of 100 iterations. The following procedure is in respect to iterative steps for a 100 simulation step (as selected for MCS).

- The average household load profiles with 5% of standard deviation are considered. EVs are randomly allocated to all household in the feeder. Note: it is possible therefore that all EVs are allocated (and connected at the start of the feeder or they may be at the end of it. To capture, the full impact of EV, fast charging up to 11 kW is considered based on current advances in terms of an 41 kWh battery size being available in the Irish market for domestic use [3].
- For the purposes of simulation, different EV penetration levels (30%, 60% and 100%) are selected. Penetration in this regard refers to the number of EV connections relative to the number of customer connection points on the network. The EV Battery state of charge (BSOC) is randomly assigned to different households at single phase connection. Although, from the sake of simplicity, based on the allocation of the EV load on each phase in the network is calculated. It is noted that each EV BSOC pool follow different probability distributions to cater the uncertainties related to BSOC, size and location of the EV connected.
- Once the household load and EV load profiles are assigned to the each individual household in the network, load flow is executed using DIgSILENT power factory. The load flow results like

voltage, current and apparent power are stored for the simulation for probabilistic impact assessment.

- The initial load flow calculated results provide reference value from Monte Carlo simulation. MCS subroutine is developed using DIgSILENT, DPL (DIgSILENT programming Language). The 100 iteration with 5% standard deviation are calculated through MCS routine.

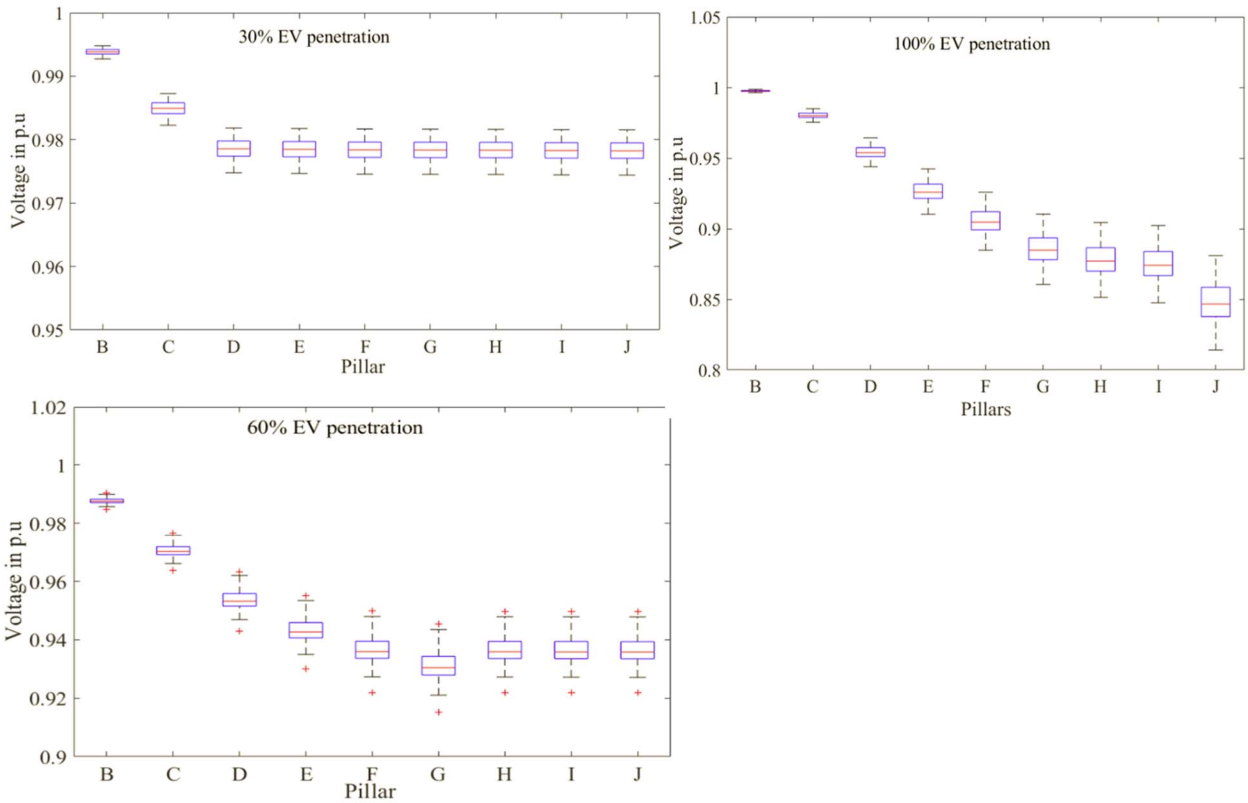


Fig. 3: Probability of Voltage drop range at each Pillar with 30%, 60% and 100% EV penetration based on MCS

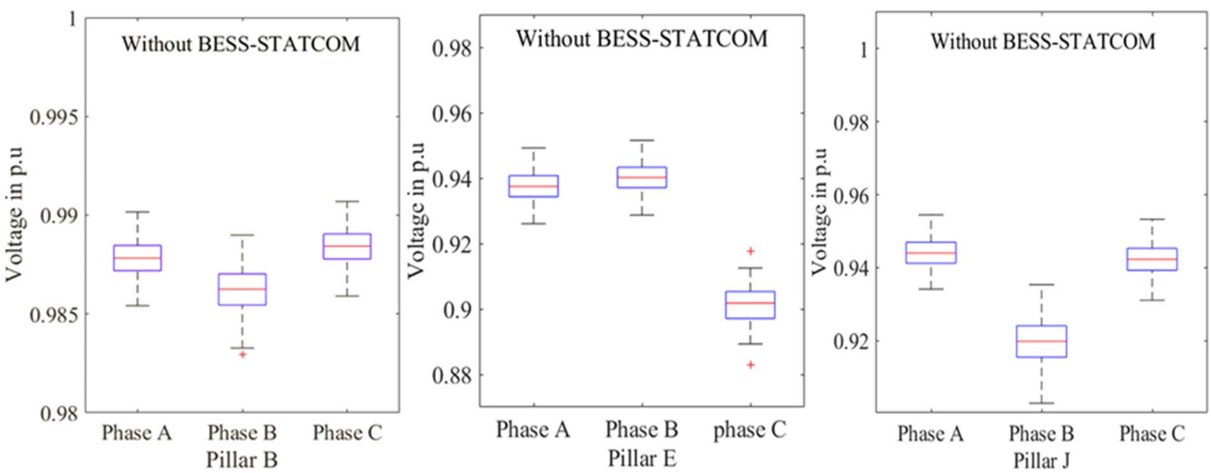


Fig. 4: Probability of Voltage drop range at each Phase, on Pillars, 100% EV penetration based on MCS

## Temporal Analysis (Proposed controlling technique)

Voltage problems can be solved by reinforcing the distribution network, although upgrading existing network requires significant amount of investment. Another prospective solution is on-load tap charger (OLTC), although in Irish/UK distribution level, OLTC's are not commonly used. OLTC can mitigate the voltage problem, but the voltage unbalance factor still remains an issue. Another prospective solution is PV inverter dispatch of reactive power. In [18], reactive power support is proposed based on inverter ratings. Although only limited reactive power support is possible due to power rating of inverter, additional power losses and importantly due to limit reactive power support, small effect on voltage profile. In [19], hybrid voltage schemes, based on real and reactive power management embedded with centralized OLTC, is discussed. The results are quiet promising but the effects of reactive power is limited and not all distribution level transformers are equipped with OLTC functionalities. In [22] the authors have also designed and briefly define the controller for D-STATCOM with improved power quality (voltage-control). [23] using a new control-algorithm-based multifunctional D-STATCOM, [24] D-STATCOM operating in current control mode (CCM), and voltage control mode (VCM) although limited to short time voltage variation experiment test result (voltage sag and dip), penetration of realistic EVs are not presented.

The STATCOM provision at distribution levels is termed as 'D-STATCOM'. D-STATCOM are employed to reduce total harmonics distortion and power quality maintenance [25, 26]. D-STATCOM provides reactive output power (capacitive or inductive) to control the voltage at given terminals and to maintain desired power flow under possible disturbances. The control requirement of the compensator depends upon power flow variation and associated requirements to stabilize power system reactions to network contingencies and dynamic disturbances. The basic compensation needs to fulfil one of two main categories: *direct voltage support* (to maintain voltage in case of disturbance) and *transient and dynamic-stability improvements* (to increase stability margin). The STATCOM in this regard, is essentially designed as a static generator to facilitate direct voltage support [27]. In the proposed control technique, '*active power control is embedded in STATCOM through battery BESS*', the battery charge is utilized to provide voltage support in the distribution network. The control equations (1) and (2) describes the voltage injection relationship in terms of the reference signals of the STATCOM [28, 29, 27] as presented in Fig. 5.

The static generator is controlled in voltage oriented coordinates (dq rotating reference frame), whereas the control inputs to the static generator are in stationary reference frame. Hence, the controlled inputs of the static generator are transformed from stationary (αβ frame) to rotating reference frame (dq frame) through park transformation [20].

$$u_d = -u1_{rin}.sinu + u1_{iin}.cosu \quad (1)$$

$$u_q = u1_{rin}.cosu + u1_{iin}.sinu \quad (2)$$

$$cosu = u_r/u \quad , \quad sinu = u_i/u$$

$u_d$ = direct voltage coordinates signal

$u_q$ = quadrature voltage coordinates signal

Where *u1= (u. (cosu+jsinu) = ur + j.ui)* is the complex voltage at the controlled bus, ur is the real component of bus voltage, ui is the imaginary component of bus voltage, $i_r$ is the real component of current and $i_i$ is the imaginary part of current.

$u_r = u1_{rin}$ = positive sequence real component of voltage in p.u.

$u_i = u1_{iin}$ = positive sequence imaginary component of voltage in p.u.

u = voltage in p.u.

I = current in p.u.

Based on the STATCOM bus connection, it is possible to calculate apparent power

$$S = u.I^* = (u_r + j.u_i).(i_r - j.i_i) = P + jQ \quad (3)$$

$$P = u_r.i_r + u_i.i_i \quad (4)$$

$$Q = u_i.i_r - u_r.i_i \quad (5)$$

The main factor responsible for voltage instability is the networks inability to meet reactive power demand [21]. In power systems, P_V (MW) and Q_V (MVAr) curves are employed as references to maintain distribution network voltage levels within acceptable tolerances. The Q_V curve represents reactive power demanded at the specific terminal as the associated voltage magnitude changes.

In the active power controller, the battery energy storage system (BESS) is assumed to be 'fully charged' and can provide active power to support network through '*Pev*', by comparing with power measurement of network '*Pmeas*'. Magnitude limitation limits the active power that can be injected into the PI controller in terms of '*ipref***'.** This reference voltage signal controls the compensator. Feedback to the compensator is facilitated through '*Vreal*' once it is 'matched' to the '*ipref*' signal. If the value of '*Pref*' is not zero then the PI controller rectifies it and sends an *vd* signal to compensator until '*Pmeas***'** and '*Vreal***'** values derive a '*Pref*' value that is zero.

In the reactive power controller, '*Vmeas***'** facilitates measurement of the three phase voltage as dynamic voltage reference at the desired location. The 'Q_V' block takes the reference voltage, '*Vmeas*', input and matches it with Q_V curve. If '*Vmeas'* is less then reference voltage stipulated by the Q_V curve then '*Qmeas'* signal is higher than '*Q'* signal. The control '*Qref' signal* is negative, which means positive '*Iqref*' signal to compensator.

The Phase-Lock-Loop (PLL block), is used to generate an output signal that relates the phase of the control variable in respect to the input reference signal. The PLL utilises a controlled oscillator that synchronizes the control variable to the reference network signal. Essentially, the *PLL* provides a reference for the voltage angle that the STATCOM employs to relate voltage and current while calculating the active and reactive powers. In general, the terminal voltage is varied through an appropriate reactive power correction, facilitated by the '$Q_{ref1}$' signal (as derived from '*Vmeas***'** input value). The varied terminal voltage is essentially compared to a fixed reference 'Vref', which through PI controller and phase matching (through the PLL) obtains the desired effective reference signal 'vq'.

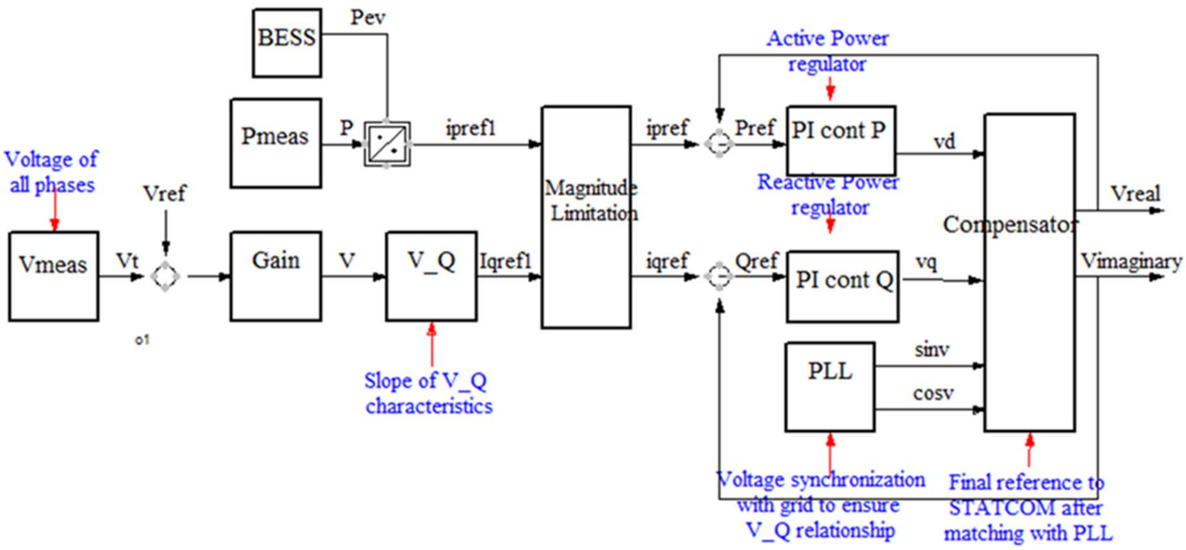


Fig. 5: Proposed STATCOM Control Scheme Block Diagram

The standard charging profiles considered for simulation and analysis are presented in Table I. The first column presents the distance travelled in kilometer before the EV requires charging. The second column relates the (charging) power consumption of the EV battery to distance travelled. The third, fourth, fifth and sixth columns indicate the requirement to achieve complete (100%) charge through different types of chargers. These columns relate the amount of charging energy required by the vehicle in respect to travel distance. In an assumption that a car travels 10 km, it will therefore require 1.4 kWh of energy and '3 phase 230V-16A' charger can provide it in 8 minutes. 'Single phase 230V-10A' charger can charge in 37 minutes. Single phase is considered. For sake of simplicity, 33.33 minutes (2000 seconds) charging time is considered, EV load connected at 500 seconds and disconnected at 2500 seconds, giving 2000 seconds to charge the EV battery. 'kW' associated with the EV charging is 3.68 kW, but to create 'a worst case scenario', 11 kW single phase is considered in the simulation(s).

It is assumed that each EV is connected at the same common point of connection (CPOC) as the household load and through a single-phase connection. Charging profiles for EVs can vary depending on battery type, charging equipment and the electricity supply network. It is also assumed that once connected, an individual EV with no charge controlling capability, charges at a rate of 11 kW up to a


assigned jointly to the European Power Electronics and Drives Association & the Institute of Electrical and Electronics Engineers (IEEE)

BSOC of approximately 95%. In other words, the charging process is dependent entirely on connection time. For this work, all EV batteries are modelled with a capacity of 20 kWh. Normally, fully electrical (20/40 kWh) and plug-in hybrid EV (8 kWh) technologies. The EV charging equipment is assumed to have a 90% efficiency rating. The charging rate of 11 kW is in excess in terms of the power delivery capabilities of existing LV distribution networks in Ireland [28]. EV batteries are modelled as constant power loads with unity power factor.

**Table I: Charging specification of EV** [29]

| **Distance travel (km)** | **Charging Energy (kWh)** | **230V/10A 2.3 kW (time)** | **230V/16A 3.68 kW (time)** | **3x230V/16A 11 kW (Time)** |
|---|---|---|---|---|
| 10 | 1.4 | 00:37 | 00:23 | 00:08 |
| 20 | 2.8 | 01:14 | 00:46 | 00:15 |
| 50 | 7.1 | 03:04 | 01:55 | 00:38 |
| 100 | 14.1 | 06:08 | 03:50 | 01:17 |
| 150 | 21.2 | 09:12 | 05:45 | 01:55 |
| 200 | 28.2 | 12:17 | 07:40 | 02:34 |

For each 500 second interval, three-phase unbalanced power flow calculations are preformed using customer demand profiles in order to ascertain the voltage level as a consequence of high penetration of EV loads. The network is simulated with time varying (hourly) household load and controlled EV charging. All the EVs are connected to the network at the same time period for 33.33 minutes duration (500 sec to 2500 sec) as shown in Fig. 6, which is based on the previously described charging rationale. The study presents a limited simulation time of 6 hours (21600 seconds) to appreciate comprehensive mitigation of voltage. By connecting all the EVs together at same time, the worst load demand increase possible in the network is created. The BESS-STATCOM is then tested on the worst possible scenarios. The concept of 'Smart charging' as it applies to EV facilitates the balancing EV of load based on prioritizing EV battery charging state. Smart charging of EV in this regard is not however implemented in this report. Instead worst case charging scenarios are considered like simultaneously charging all EVs with 11 kW charger.

The average distance passenger cars travel in Dublin is 15 km/day [5] in 24 minutes and such distances require 34.5 minutes or 2070 seconds to charge on daily basis at 3.68 kWh/single phase charger based on the flat start (fully discharge) scenario. However, in order to demonstrate the benefit of the BESS-STATCOM controlling technique, 11kW single phase charging for 34.33 minutes is considered. The worst possible network operating conditions are therefore considered. These concern the different EV loads, residential household load (with realistic conditions considered for varying residential load, on an hourly basis), EV location and initial battery SOC. Household load data vary quiet significantly during different season in year. It is assume that all EVs are connected to the network while not travelling. If an EV is travelling from 9:00-17:00, eight hour per day, the remaining are considered as being connected to the network [5]. In the absence of readily available (and reliable) EV charging data, an initial SOC is assumed. Different scenarios that relate the robustness and reliability of the network under BESS-STATCOM control strategies are possible, but one is presented for brevity.

**100% EV & 30% randomly placed DGs penetration with and without BESS-STATCOM**

The context for analysis is consistent with [8], an hourly profile representing both household load/generation demands and associated wind and solar resources over the same period (April 2012). The specific worst case scenario considered in this research is in respect to EV charging in order to highlight the advantages of this BESS-STATCOM. Fig. 6 illustrate the voltage profile at pillars J respectively in term of DG generation/EV load. BESS- STATCOM is able to maintain the voltage range between 0.95-1.05 p.u throughout 6 hours. In fact it has the effectively cut off voltage breach at pillar J, highlighted in red box. In Fig. 6 the three-phase voltage profiles of individual phases with respect to 500 seconds time interval duration over a 6 hour analysis duration (21600 seconds) are presented. All the

EVs are connected for 33.5 minutes simultaneously from duration between 500 sec to 2500 sec. When all EVs are connected simultaneously the voltage drop in all individual phases and can be seen in Fig 6. Voltage profile consideration of each individual phase at the Pillar most (physically) displaced from the substation transformer, Pillar J is prioritized in this analysis. DG/EV penetration closest to the upstream MV grid, in the context of an exemplar urban distribution network, will have less impact on voltage profile than DGs connected to the far end of the radial network. The voltage profile across the network will vary according to the location and rating of DGs/EVs. EVs/DGs are connected to the network as single phase sources, but as such, they can impact voltage level on all (three) phases with the voltage unbalance factor also being affected. Under the conditions considered (April, 2012) in terms of the consumer demand and DG (DwG and DpvG), voltage breaches were not observed until the high penetration of EV connected simultaneously in the network. The wind and solar data obtain from the resources although during six hour simulation duration time, solar generation is not available. DG profile contains total 0.34 kW of wind generation throughout the 6 hour simulation result. The DG net generation profile is included in Fig. 6, but is marginal in comparison to EV load consumption, which is approximately 0.84 MW. An average household (consumer) load of 0.495 kW is simulated. The main purpose of this analysis is to demonstrate STATCOM capability to reduce voltage drop effectively in reaction to EV load (charging) effects on the network and its capability to reduce voltage fluctuations in the network.

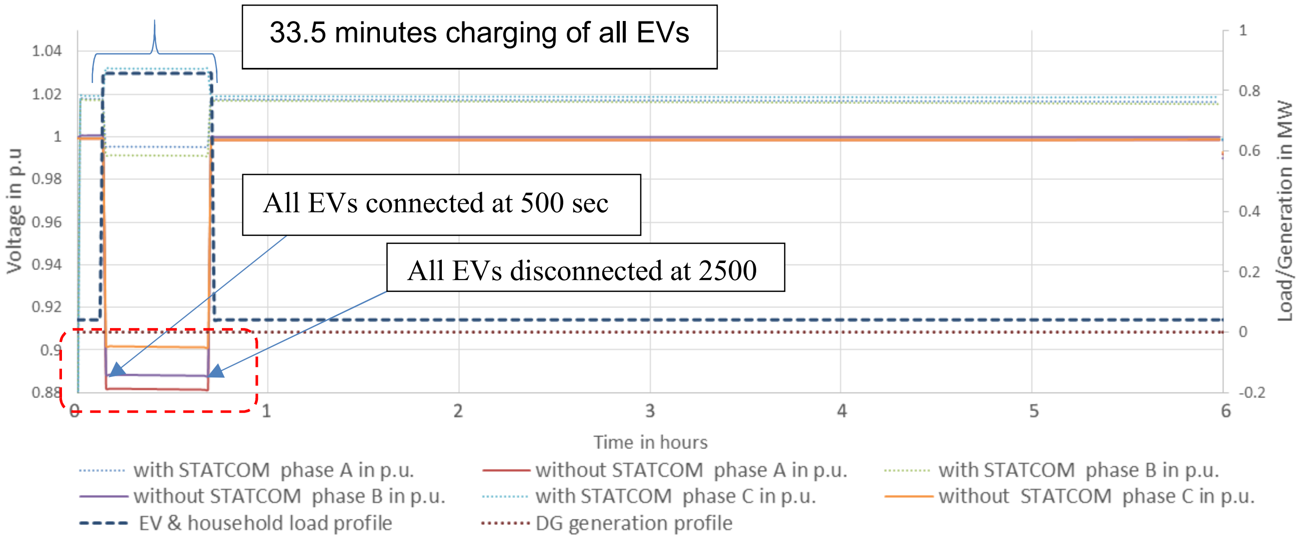


Fig. 6: Proposed Voltage with and without BESS-STATCOM at pillar J (last pillar in network) in presence of EVs and DGs

## Conclusions and future work

LV networks are designed for traditional centralized generation; they are not configured to readily accommodate decentralized generation opportunities. This paper describes mechanisms through which voltage support and possible voltage level mitigation solutions are achievable through BESS-STATCOM. In this paper first spatial analysis pinpoint the extent of voltage drop/unbalance caused by EVs, then mitigating solution is presented through dynamic modelling of BESS-STATCOM. BESS-STATCOM is used in a distribution network model to enhance the penetration level of EV and is tested against worst possible scenario, (with 100% EV penetration on same time period) the result show it can compensate the voltage level of each phase in unbalance network. The voltage limit is set 0.95-1.05 p.u as a control constraint (as defined by EN5160 – from a grid code perspective) and the associated levels are not breached while BESS-STATCOM is connected to pillar J, the most physically displaced section of the network. Optimal placement and economical justification of this device needs to be considered in future work. Currently, the distribution level custom power devices like STATCOM and Dynamic Voltage Regulator (DVR) are in testing phase and commercial availability is limited. So, economically justification is not considered in this work. Transient behavior analysis is another aspect to look into in future works. The behavior of STATCOM under unbalance faults is another aspect to be considered in further analysis. The feasibility level of penetration of the electric vehicles embedded with V2G functionality is one of the challenges that needs to be overcome for EV adoption in the energy market. BESS-STATCOM, with active power priority, could potentially support increased EV capacity on the network. For an effective implementation of the V2G concept, the efficiency of the EV battery technologies remains a concern under frequent charging and discharging cycles. Researches have shown some promising results using PV-STATCOM [30], limitation of this concept, is that it can provide limited support at nighttime (when the solar energy is not producing its rated power output). Another prospect requiring further investigation is in respect to frequency deviation mitigation in weak grids that needs further investigation.

## Bibliography


[1] U. Nation, "Population distribution,urbanization,internal migration and development: An international perspective," New York, 2011.

[2] "UITP," UITP Advance Public Transport, 2017. [Online]. Available: http://www.uitp.org/news/zeeus-report. [Accessed June 2018].

[3] "Reuters," 2017. [Online]. Available: https://www.reuters.com/article/us-britain-autos/electric-cars-win-britain-to-ban-new-petrol-and-diesel-cars-from-2040-idUSKBN1AB0U5. [Accessed May 2018].

[4] P. Bruge, U. Guida and M. V. d. B. Goralczyk, "ZeEUS eBus Report An overview of electric buses in Europe," ZeEUS project, Brussels, 2016.

[5] "Central Statistic Office," National Travel Survey 2016, 2016. [Online]. Available: http://www.cso.ie/en/releasesandpublications/ep/p-nts/nts2016/. [Accessed June 2018].

[6] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renewable and Sustainable Energy Reviews,* vol. 34, p. 501–516, 2014.

[7] J. M. Sexauer and S. Mohagheghi, "Voltage Quality Assessment in a Distribution System With Distributed Generation—A Probabilistic Load Flow Approach," *IEEE Transactions on Power Delivery,* vol. 28, no. 3, pp. 1652-1662, 2013.

[8] Y. Chen, J. Wen and S. Cheng, "Probabilistic Load Flow Method Based on Nataf Transformation and Latin Hypercube Sampling," *IEEE Transactions on Sustainable Energy,* vol. 4, no. 2, pp. 294-301, 2013.

[9] T. Williams and C. Crawford, "Probabilistic load flow modeling comparing maximum Entropy and Gram-Charlier Probability Density Function Reconstructions," *IEEE Transactions on Power Systems,* vol. 28, no. 1, 2013.

[10] C.-L. Su, "Probabilistic load-flow computation using point estimate method," *IEEE Transactions on Power Systems,* vol. 20, no. 4, pp. 1843-1851, 2005.

[11] K. Sunderland, M. Coppo, M. Conlon and R. Turri, "A correction current injection method for power flow analysis of unbalanced multiple-grounded 4-wire distribution networks," *Electric Power Systems Research,* vol. 132, pp. 30-38, 2016.

[12] H. Markiewicz and A. Klajn, "Voltage Disturbances,Standard EN 50160-Voltage Characteristics in Public Distribution Systems," Copper Development Association, 2004.

[13] K. Sunderland, M. Coppo, M. Conlon and R. Turri, "A correction current injection method for power flow analysis ofunbalanced multiple-grounded 4-wire distribution networks," *Electric Power Systems Research,* vol. 132, p. 30–38, 2016.

[14] E. Skoplaki, A. Boudouvis and J. Palyvos, "A simple correlation for the operating temperature of Photovoltaic modules of arbitrary mounting," *Solar Energy Materials & Solar Cells,* vol. 92, pp. 1393-1402, 2008.

[15] CER, "Comission for Energy Regulation," 2017. [Online]. Available: http://www.cer.ie/electricity-gas/electricity. [Accessed 30 May 2018].

[16] S. Pukhrem, M. Basu and M. Conlon, "Probabilistic Risk Assessment of Power Quality Variations and Events Under Temporal and Spatial Characteristic of Increased PV Integration in Low-Voltage Distribution Networks," *IEEE Transactions on Power Systems,* vol. 33, no. 3, pp. 3246 - 3254, 2018.

[17] A. Safayet, P. Fajri and I. Husain, "Reactive Power Management for Overvoltage Prevention at High PV Penetration in Low Voltage Distribution System," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Montreal, QC, Canada , 2015.

[18] N. Efkarpidis, . T. De Rybel and . J. Driesen, "Technical assessment of centralized and localized voltage control strategies in low voltage networks," *Sustainable Energy, Grids and Networks,* vol. 8, pp. 85-97, 2016.

[19] C. Kumar and M. K. Mishra, "A Voltage-Controlled DSTATCOM for Power-Quality Improvement," *IEEE Transactions on Power Delivery,* vol. 29, no. 3, 2014.

[20] C. Kumar and M. K. Mishra, "A Multifunctional DSTATCOM Operating Under Stiff Source," *IEEE Transactions on Industrial Electronics,* vol. 61, no. 7, pp. 3131 - 3136, 2014.

[21] C. Kumar and M. K. Mishra, "Operation and Control of an Improved Performance Interactive DSTATCOM," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 10, 2015.

[22] M. Srinivas, I. Hussain and B. Singh, "Combined LMS–LMF-Based Control Algorithm of DSTATCOM for Power Quality Enhancement in Distribution System," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* vol. 63, JULY 2016.

[23] B. Singh, S. K. Dube and S. R. Arya, "Hyperbolic tangent function-based least mean-square control algorithm for distribution static compensator," *IET Generation, Transmission & Distribution,* 30th May 2014.

[24] "Static Generator ElmGenStat-Technical reference documentation," DIgSILENT GmbH, 2016.

[25] J. Cepeda, E. Aguero and D. Colome, "Programing of Simplified Modls of Flexible Alternating Current Transmission System (FACTS) Devices Using DIgSILENT Simulation Language," in *Power Factory Applications for Power System Analysis*, Springer, 2014, pp. 391- 420.

[26] J. Rueda, A. Korai, j. Capeda, I. Erlich and F. Longatt, "Implementation of SImplified Models of DFIG-Based Wind Turbines for RMS-Type Simulation in DIgSILENT PowerFactory," in *Power Factory Applications for Power System Analysis*, 2014.

[27] R. Herrera and P. Salmerón, "Instantaneous Reactive Power Theory: A Reference in the Nonlinear Loads Compensation," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* vol. 56, no. 6, JUNE 2009.

[28] SEAI, "Sustainable Energy Authority of Ireland," SEAI, 5 June 2015. [Online]. Available: https://www.seai.ie/grants/electric-vehicle-grants/electric-vehicle-home-charger-grant/. [Accessed 2018].

[29] "Danskelbilkomite," June 2018. [Online]. Available: http://www.danskelbilkomite.dk/ladetstandard.htm.

[30] R. K. Varma and R. Salehi, "SSR Mitigation With a New Control of PV Solar Farm as STATCOM (PV-STATCOM)," *IEEE Transactions on Sustainable Energy,* vol. 8, no. 4, pp. 1473 - 1483, 2017.