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A State-of-The-Art on Power Quality Enhancement Techniques: Present Scenario and Future Challenges

Alok Jain, M.K. Verma

Abstract: Supplying quality power to consumers have been of great concern for power researchers and utilities since last few decades. Power quality issues include voltage sag/swell mitigation, harmonics reduction, load balancing, voltage flicker elimination, and fault current limiting. Various control strategies have been suggested in the literature for power quality improvement. Custom power devices are quite useful in power quality enhancement. Research on power quality enhancement has mostly concentrated on offline studies. Efforts are required to be made in power quality enhancement of real-time systems. In this paper, a survey has been presented on power quality enhancement techniques in the present scenario. The article also suggests an investigation of the role of smart metering and Phasor Measurement Units (PMUs) for power quality enhancement of real-time systems in intelligent grid architecture.

Keywords* : *Harmonics, Load balancing, Power quality, Smart grid, Voltage flicker, Voltage sag.

Nomenclature Used-
RMS- Root Mean Square
PMU- Phasor Measurement Unit
DVR- Dynamic Voltage Restorer
FACTS- Flexible AC Transmission System
UPQC- Unified Power-Quality Conditioner
UPQC-Q- Reactive Power- Unified Power-Quality Conditioner
DSTATCOM- Distribution Static Compensator
FCL- Fault Current Limiter
ANF- Adaptive Notch Filter
IAF- Inductively Active Filtering
APF- Active Power Filter
AHCC- Adaptive-Hysteresis Current Controller
STATCOM- Static Compensator
ANFIS- Adaptive Neuro-Fuzzy Inference System
TSC-TSR- Thyristor Switched Capacitor- Thyristor Switched Reactor
ULTC- Under Load Tap Changer
LV- Low Voltage
ANN- Artificial Neural Network
SVC- Static VAr Compensator
HPF- Hybrid Power Filter
EPLL- Enhanced Phase-Locked Loop
DCC- Dynamic Capacitor Compensator

PWM- Pulse Width Modulation
MPFC- Modulator Power Filter Compensator
PID- Proportional-Integral-Derivative
SSFC- Static Switched Filter Compensator

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Alok Jain, Department of Electrical Engineering, Pandit Deendayal Petroleum University, Raisan, Gandhinagar 382007, Gujarat, India. Email: alok.jain@sot.pdpu.ac.in

M.K. Verma#, Department of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi 221005, Uttar Pradesh, India. Email: mkverma.eee@iitbhu.ac.in

VSC- Voltage-Source Converter
RES- Renewable Energy Source
ESS- Energy Storing System
PLL- Phase-Locked Loop
FCTCR- Fixed Capacitor Thyristor Controlled Reactor
FES- Flywheel Energy Storage
PI- Proportional-Integral
SCC- Short Circuit Capacity
ES- Electric Springs
GDC- Generalized Droop Control
MOV- Metal Oxide Varistor
SRFCL- Series Resonant Fault-Current Limiter
SSFCL- Solid-State Fault Current Limiter
SCR- Silicon Control Rectifier
FCL-DVR- Fault Current Limiter- Dynamic Voltage Restorer
ADC- Analog-to-Digital Convertor
GPS- Global Positioning System
CSU- Clock Synchronization Unit
PPS- Pulse Per Second
DFT- Discrete Fourier Transform
μPMU- Micro-Phasor Measurement Unit
PDC- Phasor Data Concentrator

I. INTRODUCTION

Maintenance of power quality is quite challenging for power utilities. Consumers must get satisfaction for the electricity charges paid by them. However, power quality deteriorates due to several problems in distribution/ transmission networks such as short circuits, equipment failures, switching of loads.

The various Power quality issues comprises of sag/swell, harmonics, load unbalancing, voltage flicker, equipment failure/disruption of supply to consumers due to fault current. A voltage sag/dip is caused due to reduction in duration of RMS voltage between 10 and 90% of the duration of the one half up to 1 minute. Voltage swell is the opposite of voltage sag. Voltage sag/swell may harm the performance of sensitive loads such as tripping of induction motors; reduce of manufacturing in automatic methods. Cause of voltage sag/swell includes the occurrence of the short circuit, starting and overloading of electric motors. Moreover harmonic voltages besides current in power systems may be caused by the presence of nonlinear burden such as electronic ballasts, computer power supplies etc. Presence of harmonics may cause more heat in the apparatus and conductors, also inconstant speed drives along with the pulse of motors. Presence of harmonics may cause rise warming in apparatus and conductors, backfiring in flexible hustle drives and torque pulses in motors.

Presence of unbalanced loads in the power system may cause increased line losses and equipment heating's due to the presence of negative sequence components. Unbalanced loading may occur due to switching of unevenly distributed single-phase loads, the occurrence of unsymmetrical faults, and open circuit in one or two phases. Voltage flickers may be caused by arc lamps, arc furnaces, switching of large motors. Voltage flicker may have a high impact on human health, including stress on the eyes, headaches, and migraines. The voltage flicker may also affect the performance of electronic equipment and lamps. The occurrence of various types of faults may lead to the flow of overcurrent in one or more phases leading to equipment failures, disruption of supply to consumers, loss of production.

Different control strategies have been suggested in the literature for enhancing power quality of networks. This paper presents a brief survey of existing methodologies proposed in the literature to consider mitigation in some of the power quality problems. Research on power quality issues has mainly focused on offline studies. Power quality enhancement of a real-time system is still a challenge to researchers and utilities. This paper suggests the possible role of smart metering and placement of PMUs in power quality enhancement of real-time systems.

This paper is separated into 8 sections. Section I presents major power quality issues, their reasons and effects on electrical networks and living beings. Section I sets the aim of the paper. Section II presents various control strategies for voltage sag/swell mitigation. Section III presents different steps that may be taken for harmonics reduction in power system networks. Section IV presents some of the methodologies that may be adopted for load balancing. Section V presents some of the techniques used for voltage flicker elimination. Section VI presents few fault current limiting strategies. Section VII sets future challenges for researchers and utilities to address power quality issues for real-time systems in smart grid architecture, and finally, Section VIII presents conclusions of the paper.

II. VOLTAGE SAG/SWELL MITIGATION

A fresh sag discovery technique for the line-interactive DVR is planned [1,2] to reduce voltage sag/swell. A fast compensation voltage sag using DVR has been proposed in [3,4], which takes a compensation time of 2ms. Performance of FACTS devices have been compared in [5] for the enhancement of voltage sag in a huge power arrangement. A regulator arrangement founded on minimum active power injection is proposed in [6] for voltage sag mitigation using UPQC-Q. Performance of DSTATCOM and DVR have been compared for the mitigation of voltage sag/swells, load voltage control, harmonic distortions [7,8]. A new method has been introduced to find the way for voltage in static compensator DSTATCOM which is then compared with the normal mode DSTATCOM, and can be found that power factor we get is unity during regular process at the load terminal. This algorithm results in lower rated DSTATCOM to mitigate voltage sag [9,10]. A novel situation for the generation of signal for UPQC is considered to mitigate power quality sensitive glitches [11-13]. Placement of UPQC has been considered to diminish sag and harmonics as a result of grid-interconnection along the turbine, and it is found out that with the interconnection of the grid, UPQC well compensate current and voltage problems of sensitive loads [14]. An advanced technique has been introduced using FCL for the compensation of voltage sag [15]. Figure 1 shows the current literature available on voltage sag/swell mitigation.

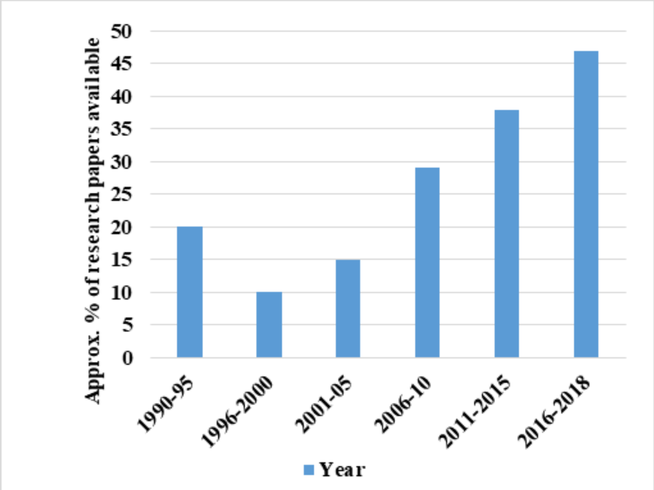

Figure 1 Current literature available on voltage sag/swell mitigation

III. HARMONICS REDUCTION

Harmonic reduction using ANF has been proposed [16-19], which converts the signal of power into its elements without considering the location of frequencies. An IAF method has been suggested to minimize harmonics caused due to non-linear loads in distribution networks [20]. IAF proposed in [20], is effective in harmonics reduction, in demand as well as supply side. An altered compact order numerical ANF that is used to withdraw harmonic content which is the current or voltage and is also used to compensate to non-required frequency component, and is also used for compensation of unwanted frequency components has been proposed [21]. For switching impulse generation, an improvement in APF has been made by using AHCC and it is found that this technique enhance the quality of power in reaction compensation of power due to non-linear distribution link [22]. A controller has been designed using an artificial neural grid which uses an algorithm that has weights in widrow-hoff is to make adaptive quest vigorous mesh which is used to compensate the other unbalanced loads like the power factor, harmonics currents etc [23]. For the improvement of quality of power in grid + wind system, the STATCOM method have been introduced to reduce the harmonics [24,25]. Different placements of FACTS have suggested that the quality of power enhances if the generators of wind are interlinked with the grid systems [26-28]. A STATCOM with ANFIS system, having ULTC transformer in connection with harmonic filter have been proposed that helps in reducing the harmonics [29-31]. TSC-TCR with quick changing of loads at the LV level of distribution is planned to cut back the harmonics discharged by the distribution system [32], in which the logic of fuzzy and ANN is used to find solutions of non-linear delay angles that are used in the triggering of thyristors in TCR. A device is also used known as SVC is proposed for controlling VAr and also helps in reducing harmonics [33-35]. Table I shows various methodologies/ controllers suggested in the literature for harmonics reduction.

**TABLE I.
METHODOLOGIES/CONTROLLERSSUGGESTED FOR HARMONICS REDUCTION**

Methodologies/Controllers for harmonics reduction	Reference Numbers
• ANF	16-19,21
• IAF	20
• APF • Adaptive-Hysteresis Current Controller	22-23
• STATCOM	24-25
• FACTS	26-28
• ANFIS	29-31
• Fuzzy	32
• SVC	33-35

IV. LOAD BALANCING

Balanced/symmetrical is the other name used for 3-phase system of power, if the voltage and current are phase shifted to 120° having same amplitude to each other. When not meet in any of the condition that is known as unbalanced or asymmetrical. Load balancing using a HPF has been proposed in [36]. Proposed power filter comprises of many layers of the active filters and passive filters which are interlinked in parallel with the load and, with this planning, the active filter helps in the harmonic compensator feature of the passive filter and, therefore helps in load balancing [37-38]. Placement of DSTATCOM fed by an isolated 42.5kVA alternator has been suggested for load balancing with respect to voltage regulation in distribution system [39,40]. Another method depends on EPLL for DSTATCOM is used to provide balancing of loads and other details as discussed above, which includes power factor, harmonics etc. and it has been found out that with the use of EPLL, DSTATCOM performance gets enhanced [41,42]. A DCC strategy has been presented using FACTS devices for 138kV system that helps in voltage compensation and load balancing [43,44]. A novel voltage stabilization and balancing of loads have been introduced using PWM switched MPFC that is controlled with a PID controller [45,46]. This can also be achieved by extending the energy interface and also using controls that can be obtained by changing the other requirements for voltage regulator. A reduced-rate SSFC have been introduced for the enhancement of the quantities again as discussed above which includes power factor, voltage stability for the Smart-Grid Distribution Networks which are controlled by a device that is run by the enhanced VSC controller [47]. Multilevel bridge STATCOM has been used in a 3-phase system which is presented by the extent of the unbalance of voltage [48]. It has been found that control scheme proposed in [48], can also be used in the multi-level converter as an application of the PV inverter systems. A new plan for achieving the full benefits of installing grid when interfaced with inverters in electrical power system has been given [49]. And, this inverter can be used as a power converter that helps in inserting power to the grid that's generated from the RES and can also be used as APF to mitigate the distortion in current, load current harmonics, load demand and load neutral current. An ESS for reducing unbalances in voltage has been developed & it is found out, that this helps in up the potency of the electrical networks [50]. An ANN-based supervisor for the current regulator of the active power filter has been projected in [51] that are trained offline using knowledge from the traditional PI controller which helps in balancing of the loads. Table II shows the recent literature available on load balancing using different methodologies/compensation techniques.

**TABLE II.
METHODOLOGIES/CONTROLLERS SUGGESTED FOR LOAD BALANCING**

Methodologies/Controllers for load balancing	Reference Numbers
• Filter	36-38,50
• DSTATCOM	39-42
• FACTS	43-44
• MPFC	45-46
• SSFC	47
• STATCOM	48-49
• ANN	51

V. VOLTAGE FLICKER/GLIMMER ELIMINATION

Hefty tons can significantly alter the load currents in an electrical system. Voltage glimmer happens once substantial loads are occasionally switched on and off in a system. Variations in voltage will happen if the SCC of the system is not large enough. Initially, huge motors would like associate inrush of current that causes a discount to voltage. This reduction in voltage might cause an evident glimmer on the illuminating circuits that are coupled to the similar power theme. Numerous implementations of a non-linear ANF, which functions built on the idea of an improved PLL accessible in [52] is used to remove the voltage glimmer. Numerous implementations of filter that helps in detection of harmonics, variations/fluctuations, disturbances, and demodulation of phase or magnitude for the glimmer valuation have been presented based on the time-domain simulations, and it has been shown that the flexibility of the filters makes it vigorous w.r.t minor differences in the power frequency. An 11-level multilevel converter STATCOM with PWM switch is employed to get rid of glimmer and unbalancing of loads (unbalanced electric arc furnace load) has been presented [53]. This scheme shows better results as compared to the ANF scheme. The performance of the converter with PWM introduced in [53], has been compared with a multilevel STATCOM, i.e. accustomed mitigate voltage flicker induced by an electrical arc chamber and for this, a novel non-linear control has been proposed to provide improved control for RMS voltage [54].

Use of FCTCR, a 6-impulse VSC associated with a 12-impulse STATCOM based on VSC in connection with RLC filter have been presented for total mitigation of voltage glimmer deprived of harmonics [55]. A FES has been used to mitigate glimmer glitches introduced by wind generation into micro-grids. Simulation tests on the behavior of the FES device are analyzed, once it works together with wind power within the small electrical grid [56-58]. An effective model supported by adjustive PI control are bestowed in [59], which might self-adjust the control gains throughout a flicker disturbance so the performance perpetually matches a desired response for STATCOM method. An inclusive plan for ES has been suggested that contributes in controlling of both frequency & voltage in [60], for the mitigation of flicker. It adopts the management of phase and amplitude that severally alter the active power and also the reactive power of the system [61]. A framework based on the ANFIS has been developed for flicker elimination [62]. It has been shown that this smart control assembly rigorously tracks the GDC dynamic behavior, and found after the contrast that it exhibits high capability and desirability response for various load modification situations. Figure 2 shows the current literature available on voltage flicker elimination.

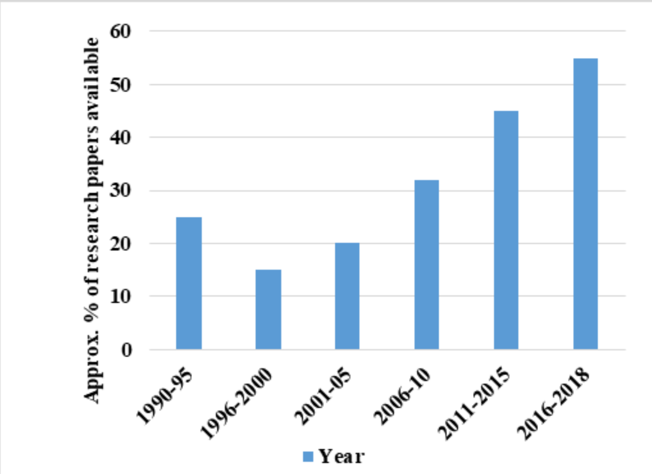

Figure 2 Current literatures available on voltage flicker elimination

VI. FAULT CURRENT LIMITING

Fault-Current Limiters by means of huge-temperature superconductors offers a remedy to regulate the levels of fault-current on electrical power system. These fault-current regulators or high-impedance modifiers, helps in reducing fault-current deprived adding impedance to the circuitry through usual process. MOV in shunt with capacitor, with frequency tuned LC circuit has been imposed for limiting the fault-current [63]. The influence of SRFCL on enhancement of power quality of distribution system has been analyzed with MOV for good results [64]. A SSFCLs to decrease tall short-circuit current stages is planned by introducing a series impedance when the liability occurs or by turning off semiconductor devices [65]. A booming type solid-state fault present controller has been industrialized distribution-generation elements in the micro grid. Through liability incidence, an auto-triggered SCR is used that pullouts the parallel resonant circuit in the load current path [66]. The influence of the numerous SSFCLs on numerous electrical influence webs with the wind-turbine power generation has been examined [67]. A secondary plan for down-stream disruption of fault-current using an active voltage restorer in distribution line has proposed that compensates the voltage sag also limits the fault current [68]. Fast least square error digital filters helps in estimating the phase and amplitude of the measured voltages and effectively helps in reducing the impacts of noise, harmonics, and disturbances on the calculable phasor parameters that modify effective fault current interrupting even beneath arcing fault conditions [69]. A FCL-DVR used in [70-71], which has crowbar bi-directional thyristor switch across the output terminals of a conventional end-to-end DVR. During power outages, the controller will neutralize the faulty stage of the DVR and connect its crowbar thyristor that helps in limiting the fault-current.

VII. POWER QUALITY ENHANCEMENT IN SMART GRID

Research available on power quality enhancement has mainly concentrated on offline systems. In smart grid architecture, it may be quite challenging to mitigate voltage sag/swell, reduce harmonics, balance loads, eliminate voltage flicker, and limit fault current for real-time systems. Proper control strategies are to be planned to address these issues. Voltage and current phasors at different houses may be measured by smart meters, and at distribution substations, micro Phasor Measurement Units (μPMUs) [72] may be placed to get this information, which may be synchronized to Global Positioning System (GPS) clock. PMU measurements may be sent to (PDC) placed at the primary substation receiving power from the feeder. PDC may have various application software related to voltage sag/swell mitigation, harmonics reduction, load balancing, voltage flicker elimination, fault current limiting. Simulation results of this software may be utilized by optimally placed controllers such as custom power devices to automatically adjust their parameters such that power quality problems are minimized.

VIII. CONCLUSIONS

In this paper, an attempt has been made to present a brief literature survey on power quality improvement/ enhancement techniques. Various power quality enhancement methodologies such as the use of filters, FACTS devices, custom power devices, ANN, ANFIS were presented. Research on power quality enhancement has mainly focused on offline studies. This paper suggests future strategies which may be adopted in smart grid architecture to automatically control power quality problems with the help of smart metering and PMU technology for real-time systems.

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AUTHORS PROFILE

Alok Jain received his B.Tech (Hons.) degree in Electrical & Electronics Engineering from UPTU, Lucknow, India in 2010 and M.E. degree in Electrical Engineering (Power Systems & Electric Drives) from Thapar University, Patiala, Punjab, India in 2013. He is currently pursuing a degree in Electrical Engineering Department at Indian Institute of Technology (BHU), Varanasi, India. Now, he is working as an assistant professor in Pandit Deendayal Petroleum University, Gandhinagar, Gujarat. His research interests include smart grid, smart metering, microgrid, power quality, distributed generation, and renewable energy.

M.K. Verma received his B.Sc (Eng.) degree in Electrical Engineering from Regional Engineering College, Rourkela (presently National Institute of Technology, Rourkela), India in 1989, M.Sc (Eng.) degree in Electrical Engineering from Bihar Institute of Technology, Sindri, India in 1994 and PhD degree in Electrical engineering from Indian Institute of Technology (IIT), Kanpur, India in 2005. He is currently working as Professor in Electrical Engineering Department at Indian Institute of Technology (BHU), Varanasi, India. His current research interests include voltage stability studies, application of FACTS controllers, power quality, wide area monitoring system and smart grid.

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