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Dynamic Modeling and Performance Evaluation of STATCOM and UPQC to improve the power quality in IEEE 30-Bus Distribution System

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Abstract— Dynamically efficient active power filters present a promising solution to address recent challenges of power system applications. They are capable of effectively suppressing harmonics, compensating reactive power, and mitigating resonance issues. Unlike passive compensation techniques, active power filters can dynamically adapt to varying load conditions, ensuring reliable operation. Furthermore, Flexible AC Transmission Systems (FACTS) devices offer additional benefits by dynamically regulating reactive power flow under various load conditions and compensating for harmonic currents. By utilizing active power filters and FACTS devices, power systems can enhance transient and dynamic stability while effectively managing reactive power and harmonic issues. This comprehensive approach not only ensures reliable operation but also optimizes the overall performance of interconnected power systems and micro-grids.

In general, power quality problems in the micro grid can be divided into two separate categories. First, the problems that are related to the voltage delivered at the point of common coupling and include voltage harmonics, overvoltage, under voltage, voltage swell, voltage sag, voltage imbalance, voltage fluctuations, outages, etc. Second, the problems related to the current drawn from the network by non-linear loads such as electric arc furnaces, uninterruptible power supplies, speed control systems, etc., which can lead to power quality complications, including improper power factor, high reactive power, harmonic currents, unbalanced currents, etc. Therefore, in order to improve the level of power quality in a network, the proposed solutions solve the power quality problems from both perspectives and try to ensure that under any conditions of network problems, the voltage delivered to the load is standard.

***Keywords*—DISTRIBUTION NETWORK, STATCOM, UPQC, DG, FACTS, SMARTGRID.**

Introduction: Nowadays, with the high penetration of distributed generation resources in low voltage networks and with the increase of non-linear and unbalanced loads that have a major portion of the total load of a small-scale system creates many challenges in terms of power quality in these networks which requires extensive research in this field. Since the systems based on centralized production are facing two limitations, the lack of fossil fuels and the need to reduce pollution; Therefore, the importance of distributed generation resources has increased by connecting renewable energy systems to grids. In order to make optimal use of distributed generation resources, micro grids have been widely considered. Micro grids are local networks that include distributed generation sources, energy storage systems, and loads that can be operated in two grid-connected and island modes. The most important challenges facing microgrids is power fluctuation control, voltage control, power distribution control, and maintaining power quality in both grid-connected and island modes [1].

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Related Work:

Electrical power quality (EPQ) problems are an issue that is becoming increasingly important to all levels of usage such as industrial, commercial and utilities. The power quality issues include short-term events such as voltage sags, swells or even transients with duration of less than a few seconds. Power system harmonic and flicker issues also fall into the category of power quality (PQ), even though these issues tend to occur much longer intervals than sags and transients [11]. The authors [12-16] discussed voltage sag and its characteristics in detail. M.R.Alam et al. [17] proposed an algorithm for detection; classification and characterization of voltage sag and swell in electricity networks, using three-phase voltage ellipse parameters. The proposed method employs the instantaneous magnitude of three-phase voltage signals in three axes, which are separated from each other by 120^{o}.

From time to time different efforts have been carried out to provide an active and flexible solution to mitigate power quality disturbances. Before the advent of active filters, passive filters based on inductors and capacitors [22-24] were used and still used in many power transmission and distribution applications, but it has various disadvantages such as instability, fixed compensation, resonance with supply as well as loads and utility.

To overcome these drawbacks active power filters (APFs) have been used [25]. However, they are costly options for power quality enhancement because their ratings are sometimes very close to full load (up to 80%) in typical applications.

Objective:

In regards to power quality, voltage stabilization, and effective energy utilization, the utility load now faces new challenges due to the pervasive usage of distributed energy sources in the electrical grid. Remote or isolated communities, where connecting to the grid might be costly, can benefit greatly from this kind of technology. However, power distribution system disturbances, such as harmonic production and reactive power adjustment, are induced by the connecting of power electronic devices to DG systems. This work presents a simulation algorithm of a PV-WIND generating system. This system's efficiency in grid-connected mode is evaluated. The SPV-WIND system connected to the grid tested for its power quality. The proposed system's power quality for enhanced quality performance with the help of STATCOM and UPQC [1-3].

Methodology:

STATCOM is a voltage-source converter-based device that can rapidly control and regulate the reactive power output to support the grid voltage. It helps mitigate voltage fluctuations and maintain a stable grid voltage by injecting or absorbing reactive power as needed. In a solar-wind hybrid system, STATCOM can help manage the intermittent nature of renewable energy sources and stabilize the grid during sudden changes in power generation. UPQC is a combination of both a series and a shunt compensator, designed to correct multiple power quality issues simultaneously. The series part of UPQC is responsible for mitigating voltage sags and swells, harmonics, and flicker by injecting appropriate voltages in series with the load. The shunt part of UPQC compensates for reactive power imbalance, helps maintain voltage stability, and reduces harmonic distortion. UPQC is particularly effective in hybrid systems where multiple sources with varying characteristics (solar and wind) are integrated. Benefits of Using STATCOM and UPQC in Solar-Wind Hybrid Systems Enhanced Voltage Stability: Both STATCOM and UPQC can provide voltage support during sudden load change. Helping to maintain a stable grid voltage and prevent voltage collapse.

The proposed configuration is a connection of the sources to the power system through a power transformer with the integration of STATCOM and UPQC. The wind turbine (WT) system uses a its merits with Modeling of WT are presented to help us in analyzing the behavior of the investigated system. The most prominent PQ problems that arise from connecting the WT to the networks are voltage fluctuations and harmonics, which are verified later. To evaluate the effectiveness of the STATCOM and UPQC technologies, three operational scenarios are chosen. In the first scenario, the power system is connected to point which represents several SG loads, while in the second situation, the EPS is connected to point which is widely dispersed across SGs. Finally, the third scenario addresses the capability of FACTS tools to overcome transient faults and maintain the stability of the EPS.

(1) 1STATCOM and 1UPQC

Modeling and Control of Proposed Developed Systems:

Modeling and Control Structure of Investigated STATCOM System:

STATCOM units can supply Q to the EPS with a very fast response, which can be utilized to enhance voltage quality and mitigate other PQ disruptions in the EPS. These technologies can also improve the power grid’s efficiency and overall stability. It is a shunt reactive compensator that may absorb or generate Q in the EPS . Figure3.4 illustrates itsidentical circuit with the proposed control method. It transmits P and Q to the EPS, and thetransmitted power is managed via the firing angle (α) and modulation index (m) of thepulse width modulation (PWM) of the voltage source converter (VSC).

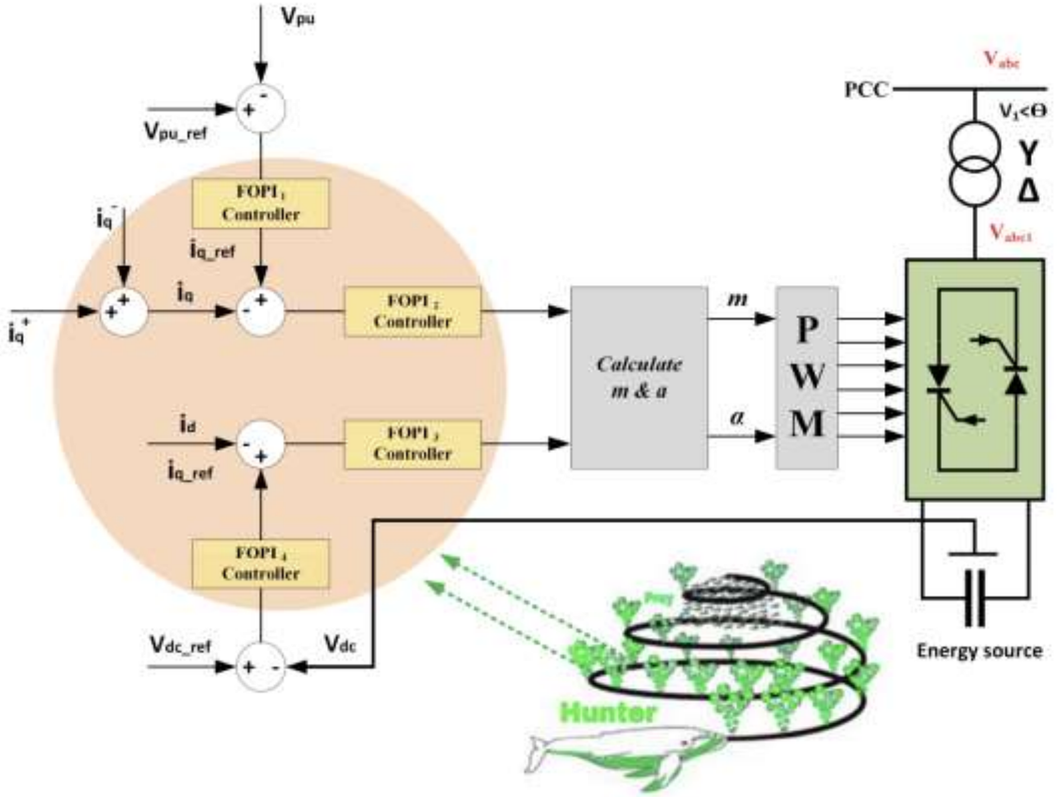

Figure 1:Configuration of WOA-based FOPI of STATCOM connected to the grid.

The equations for calculating STATCOM and VSC in the three-phase structure areas follows:

$$L\frac{d_{ia}}{dt} = -RI_a + (V_a - V_{a1})$$

$$L\frac{d_{ib}}{dt} = -RI_b + (V_b - V_{b1})$$

$$L\frac{d_{ic}}{dt} = -RI_c + (V_c - V_{c1})$$

where the system currents are Ia, Ib, and Ic. Va1, Vb1, and Vc1 are the inverter’s output voltages, while Va, Vb, and Vc are the PCC voltages. In addition, R and L are the equivalent resistance and inductance for the power transformer, respectively.

The following is a d-q frame representation of the three-phase parameters:

$$L\frac{d_{id}}{dt} = -RI_d + \omega LI_q(V_d - V_{d1})$$

$$L\frac{d_{iq}}{dt} = -RI_q + \omega LI_d(V_q - V_{q1})$$

The d- and q-axis voltages of the grid and the STATCOM are represented by the symbols Vd, Vd1, Vq, and Vq1, and !is the synchronous angular speed of the fundamental grid voltage.

The inverter’s DC link voltage can be determined as shown below:

$$V_{d1} = KmV_{dc}\sin(\delta)$$

$$V_{q1} = KmV_{dc}\cos(\delta)$$

where K is the inverter steady-state constant related to the inverter construction, m is the PWM modulation index, Vdc is the STATCOM's DC-link voltage, and *d* is the firing angle. The PWM control parameters (m and *d*) are given below:

$$m = \frac{\sqrt{V_{d1}^2 + V_{q1}^2}}{km}$$

$$\delta = tan^{-1}\frac{V_{q1}}{V_{d1}}$$

The transmitted Pac and Qac to the grid are given below:

$$P_{ac} = 1.5(V_d I_d + V_q I_q) = 0$$

$$Q_{ac} = 1.5(V_d I_q - V_q I_d)$$

Pac is taken to be zero because the STATCOM does not transfer any P to the grid and instead regulates the PCC point voltage by gripping or emancipating the Q. To prevent P from being exchanged with the power grid, d in this approach must be adjusted to a value equal to the PCCV phase angle. For the PCCV to be somewhat in the lag phase concerning d, the PCC's tiny internal losses must also be mitigated. The closed-loop control system in Figure 3.4 makes this possible. If there are internal losses, this will decrease the level of the DC link voltage, bypassing the input signals through into the WOA-based FOPIC, which will eradicate the steady-state error of the capacitor voltage, and adjust d so that its internal losses are enclosed by the grid.

Modeling and Control Structure of Investigated UPQC System

The UPQC is made up of two FACTS devices called DVR and STATCOM, as depicted in Figure 5, so it simultaneously offers their benefits [1]. Nevertheless, UPQC's approach still limits how effectively PQ may be improved. In this study, a newly created UPQC is sused to reduce current and voltage harmonics in an EPS. The mathematical model of the UPQC can be written below. The referenced three-phase currents are estimated as seen in [7].

$$\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 \; 0 \\ -\frac{1}{2}\sqrt{\frac{3}{2}} \\ -\frac{1}{2} - \sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} V_\alpha V_\beta \\ -V_\beta V_\alpha \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}$$

The obtained instantaneous load power (P and Q) is used to calculate the instantaneous power angle (j), as shown below:

$$\varphi = Sin^{-1}\frac{Q\ handeled\ by\ the\ DVR}{P\ of\ load}$$

Total power (VA) loading of the UPQC, as a function of j and the ratio between actualand rated source voltages (k), is represented by:

$$S_{UPQC}(\varphi,k) = S_{shunt}(\varphi,k) + S_{series}(\varphi,k)$$

The VA loading of the series and shunt can be determined by the following equations:

$$S_{series}(\varphi,k) = \sqrt{\left|P_{series}(\varphi,k)^2\right| + \left|Q_{series}(\varphi,k)^2\right|}$$

$$S_{shunt}(\varphi,k) = \sqrt{\left|P_{shunt}(\varphi,k)^2\right| + \left|Q_{shunt}(\varphi,k)^2\right|}$$

The V_{dc} magnitude is:

$$V_{dc} = \frac{2\sqrt{2}V_{ll}}{\sqrt{3}m}$$

The capacitor rating at the DC bus is:

$$C_{dc} = \frac{3kaV_{ph}I_{STATCOM}t}{0.5(V_{dc}^2 - V_{dc1}^2)}$$

where a is the overloading factor and t is the time required to reach its rated value after an abnormal condition.

The STATCOM interfacing inductor is:

$$L_{sh} = \frac{\sqrt{3}mV_{dc}}{12af_{sh}I_{cr,pp}}$$

The DVR interfacing inductor is:

$$L_r = \frac{\sqrt{3}mV_{dc}K_{se}}{12af_{se}I_r}$$

Where fsh and fse are the STATCOM and DVR switching frequencies, respectively. The symbol Kse is the transformation ratio of the series transformer. In this study, an enhanced FOPIC with the help of WOA is presented to enhance the UPQC control performance, as shown in Figure 5. The system detectors can be cancelled with a WOA-based FOPIC, which results in improving its dynamic response. The supply current and load voltage are monitored and adjusted to track the references that correspond to them in the d-q ref. frame via the studied control system. Using a sinusoidal PWM technique, the voltage refs. are used to generate the signals for the two components. Furthermore, a phase-locked loop (PLL) is employed to find the supply voltage's phase angle to perform coordinated transformations because the suggested technique is built in the d-q ref. frame.

A Comparison between STATCOM and UPQC Systems

As shown in Table 4, a comparison between STATCOM and UPQC is presented in terms of response time, cost, operation, benefits, drawbacks, and remarks. The points listed here were extrapolated from a number of articles, as seen in Table 4. Both STATCOM and UPQC are regarded as quick, but UPQC is better because it reacts instantly. It is important to note that for the same ratings, UPQC is costlier than STATCOM.

Power Flow Equations and Newton-Raphson Method

To determine the operating state of an electrical power system, load flow analysis is performed and power flow equations can be obtained with the procedure as defined in . Now let $\boldsymbol{Vn}$ and $\boldsymbol{In}$be the phasor voltage and current at bus n

$$\boldsymbol{V_n} = V_n e^{j\theta_n}$$
$$\theta_{nm} = \theta_n - \theta_m$$
$$Y_{nm} = G_{nm} + jB_{nm}$$

For an AC system, injected current at bus n is

$$\boldsymbol{I_n} = \left(\sum_{m=1}^{N_{Bus}} Y_{nm} \boldsymbol{V_m} \right)$$

Then, injected complex power at bus n becomes

$$S_n = \boldsymbol{V_n} \boldsymbol{I_n^*}$$
$$= \boldsymbol{V_n} \left(\sum_{m=1}^{N_{Bus}} Y_{nm}^* \boldsymbol{V_m^*} \right)$$

Using (5) in (7) gives that

$$S_n = \sum_{m=1}^{N_{Bus}} V_n V_m e^{j\theta_{nm}} (G_{nm} - jB_{nm})$$
$$= \sum_{m=1}^{N_{Bus}} V_n V_m (cos\theta_{nm} + jsin\theta_{nm})(G_{nm} - jB_{nm})$$

Equation can be resolved into real and imaginary parts to have active and reactive power equations

$$P_n = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} cos\theta_{nm} + B_{nm} sin\theta_{nm})$$

$$Q_n = \sum_{m=1}^{N_{Bus}} V_n V_m (G_{nm} sin\theta_{nm} - B_{nm} cos\theta_{nm})$$

Now, suppose there are n nonlinear set of functions $(x) = 0$, roots x at kth iteration which is an $nx1$ vector can be obtained by utilizing Taylor Series [42]

$$x^{k+1} = x^k - [J(x^k)]^{-1} F(x^k)$$

Where nxn Jacobian matrix is

$$J(x) = \begin{bmatrix} \frac{dF_1}{dx_1} & \cdots & \frac{dF_1}{dx_n} \\ \vdots & \ddots & \vdots \\ \frac{dF_n}{dx_1} & \cdots & \frac{dF_n}{dx_n} \end{bmatrix}$$

Then, rearranging (10) gives

$$\Delta x^k = x^{k+1} - x^k = -[J^k]^{-1} F(x^k)$$

After finding Δxk, one can proceed to next iteration with (13) and this iterative procedure is applied until the convergence is reached.

$$x^{k+1} = x^k + \Delta x^k$$

Newton-Raphson iterative solution procedure can be applied to power flow equations as well. First, implementation of Newton-Raphson iteration in an AC system is going to be explained and afterwards it is going to be extended for a hybrid AC/DC system.

4. Result and Discussion:

Table 1: Best bus Location for 1 STATCOM and 1 UPQC placement

Bus Location of STATCOM/UPQC		Voltage Inserted by STATCOM/UPQC		Voltage Angle of STATCOM/UPQC		Power Inserted by STATCOM/UPQC		
STATCOM 1	UPQC1	STATCOM 1	UPQC 1	STATCOM 1	UPQC 1	STATCOM 1	UPQC 1	
Bus1	Bus2	Vsh1 (p.u.)	Vsh2 (p.u.)	Theta1	Theta1	Psh (p.u.)	Psh (p.u.)	MSE
17	14	1.00	0.99	-15.86	-15.44	0.05	0.11	0.021
28	19	0.99	1.00	-11.53	-16.68	0.13	0.02	0.022
30	17	1.00	0.99	-18.29	-15.61	-0.03	0.12	0.022
24	10	1.01	0.97	-16.88	-15.42	-0.13	0.29	0.023
12	25	0.97	1.00	-14.79	-16.70	0.35	-0.05	0.023
16	18	0.99	1.00	-15.20	-16.77	0.14	-0.01	0.023
15	14	0.99	0.99	-15.83	-15.53	0.08	0.09	0.024
15	20	0.98	1.00	-15.66	-16.77	0.18	-0.05	0.024
25	24	1.00	1.00	-16.00	-16.35	0.02	-0.02	0.025
12	22	0.96	1.01	-14.73	-16.61	0.38	-0.07	0.026
16	24	0.98	1.01	-15.05	-16.64	0.18	-0.06	0.026
24	16	1.01	0.98	-16.64	-15.05	-0.06	0.18	0.026
27	20	1.00	1.00	-15.57	-16.45	0.04	0.03	0.027
16	10	0.99	0.99	-15.36	-15.64	0.10	0.09	0.027
29	21	1.00	0.99	-17.10	-16.09	-0.01	0.06	0.027
26	27	1.00	0.99	-17.38	-15.51	-0.05	0.08	0.027
21	20	1.00	1.00	-16.14	-16.45	0.04	0.03	0.027
29	22	1.00	0.99	-17.13	-15.73	-0.02	0.07	0.028
15	25	0.98	1.00	-15.69	-16.30	0.15	-0.02	0.028
24	17	1.01	0.99	-16.60	-15.58	-0.06	0.14	0.028

Table 2: Bus location STATCOM 1=Bus 17, UPQC 1=Bus 14

BUS	V_{BUS}	$Theta_{BUS}$	BUS	V_{BUS}	$Theta_{BUS}$	BUS	V_{BUS}	$Theta_{BUS}$
1	1.06	0.00	11	1.07	-14.11	21	0.99	-16.31
2	1.04	-5.37	12	1.03	-15.16	22	1.00	-16.08
3	1.02	-7.50	13	1.06	-15.16	23	0.99	-16.32
4	1.01	-9.25	14	1.00	-15.51	24	0.98	-16.41
5	1.01	-14.21	15	1.00	-16.03	25	0.99	-16.21
6	1.01	-11.06	16	1.01	-15.65	26	0.98	-16.65
7	1.00	-12.88	17	1.00	-15.89	27	1.01	-15.80
8	1.01	-11.86	18	0.99	-16.68	28	1.01	-11.73
9	1.03	-14.11	19	0.99	-16.86	29	0.99	-17.07
10	1.01	-15.76	20	0.99	-16.65	30	0.98	-17.98

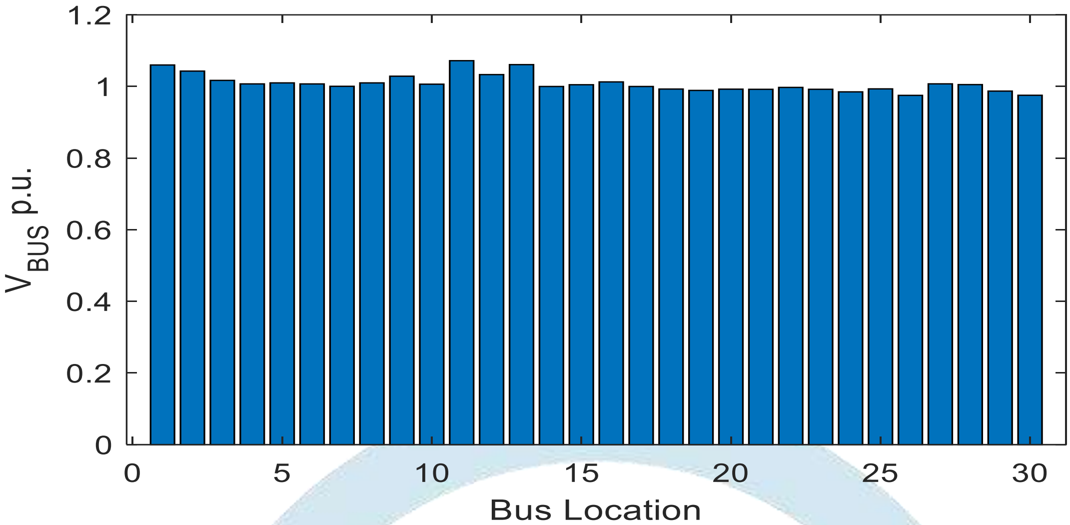

Figure1 : Bus Voltage for STATCOM 1=Bus 17, UPQC 1=Bus14

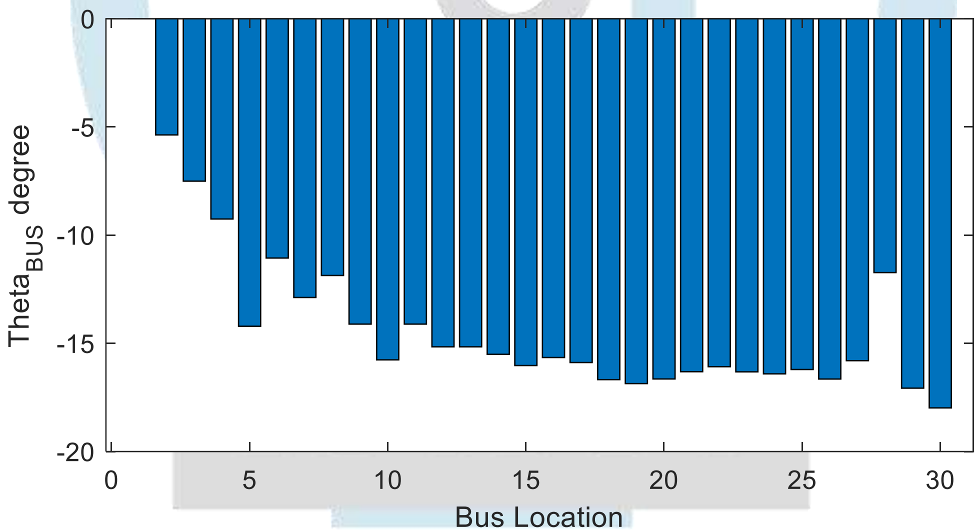

Figure 2: Bus Voltage angle (Theta) in degree STATCOM 1=Bus 17, UPQC 1=Bus14

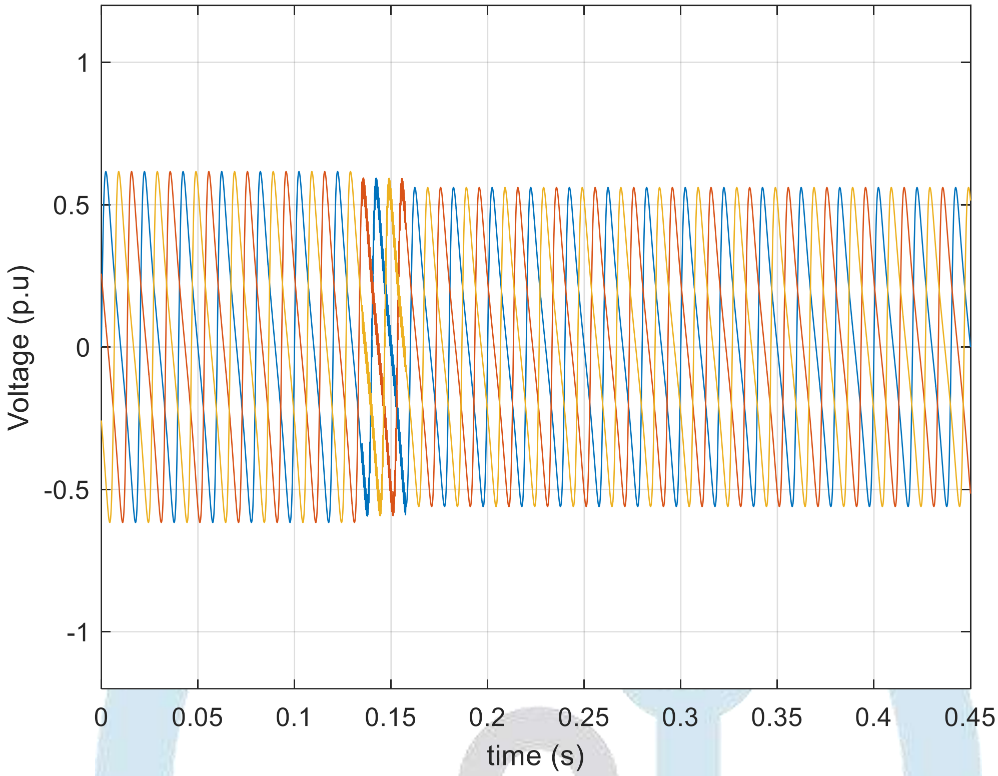

Figure 3: Fault Bus Voltage with respect to time for location STATCOM 1=Bus 17, UPQC 1=Bus

Conclusion and future scope:

Electrical power quality (EPQ) problems are an issue that is becoming increasingly important to all levels of usage such as industrial, commercial and utilities. The power quality issues include short-term events such as voltage sags, swells or even transients with duration of less than a few seconds.

This work has focused on power quality problems in the micro grid that may be divided into two separate categories. First, the problems that are related to the voltage delivered at the point of common coupling and include voltage harmonics, overvoltage, under voltage, voltage swell, voltage sag, voltage imbalance, voltage fluctuations, outages, etc. Second, the problems related to the current drawn from the network by non-linear process of uninterruptible power supplies, which can lead to power quality complications, including improper power factor, high reactive power, harmonic currents, unbalanced currents, etc. Therefore, in order to improve the level of power quality in a network, the solutions is proposed for use of multiple types of FACTS devices to solve the power quality problems from both perspectives and try to ensure that under any conditions of network problems, the voltage delivered to the load is standard.

The results are demonstrated in terms of sag, swell, T.H.D. and short circuit current for IEEE 30 bus system. In future involvement of meta heuristic optimization approach may be used to set the rating of FACT devices and the number of FACTS device may further be revised for different combinations.

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