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Power Quality Analysis And Voltage Sag Indices Using UPQC Under Various Fault Conditions

The expanding manipulation of non linear loads in the electrical power distribution system is intensifying the distortions in the current and voltage waveforms. Besides, the distribution system in the network of power system is unbalanced due to unsymmetrical faults. Also, with the insertion of Distributed Generation (DG s) into the power system, the level of fault current is increasing, which causes some power quality(PQ) issues in the distribution system. Voltage sag, swell and harmonics are the major power quality issues and the UPQC is considered as an effective device to compensate them. This paper describes about the voltage sag, current, real and reactive power in the distribution system during fault, prefault and post fault conditions. Three different fault conditions namely single line to ground fault(LG), double line to ground fault(LLG), and Three phase to ground fault(LLLG) are considered and various system indices such as sag score, Voltage sag energy index, Voltage Sag Lost Energy index, Voltage Sag Severity, Phase Voltage Unbalance Rate and power factor are analyzed. Also the performance analysis of THD is carried out in the distribution system. The potency of UPQC scheme is illustrated using MATLAB/SIMULINK environment.

Keywords: UPQC, Fault Analysis, THD, Voltage sag indices.

1. Introduction

Continuous supply of power to the consumers and keeping the voltage magnitude with in the acceptable limits is one of the prime power system constraints [1]. Presently, power systems have been pronounced and have become more complex as before, due to the inflating demand for electrical power. This ever increasing demand for electrical power may give rise to the fault current occurring due to short circuit in the power system and in some cases, may exceed the allowable level and may damage the equipment, particularly, the circuit breaker[2]. With the expansion of non linear loads, the issues like harmonics load compensation, reactive power management are appearing to be the inherent problems[3]. The present electric power industry is facing the problem of continual power supply to system as well as facing the challenge to provide better secured system, while maintain the good power quality. Power quality can be clarified as many issue expressed in terms of voltage, current or frequency variation which leads in collapse and disoperation of consumer apparatus. According to requisites or environmental situation, the term PQ issues may have various meanings and importance[4]. State-of-the-art power electronic technology is nearly emerging technologies which have attracted attention of many researchers in obtaining effective solution in enhancement of power quality. The present power system consists of various types of power quality problems such as voltage sag, voltage swell, harmonics, transients, oscillations, interruption, flicker, voltage imbalance etc[4]. The arc furnaces are the main cause of inducing high amount of harmonics into the system. The cause of such disturbances is sudden switching of load, faults occurring into the systems, starting of motor, and load variation during generator operation, non linear loads used into power system and

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the arc furnaces. Also, insertion of Distributed Generators (DG) into the power system leads to the power quality issues such as voltage flicker, voltage regulation, harmonics and voltage sag which rely on the operation of the distribution system and characteristics of DG. In addition insertion of DG and three phase symmetrical and unsymmetrical faults also gives rise to fault current level in the electrical power system[6].

Power quality issues such as harmonics are mainly caused due to system resonance and power electronic switching of loads, which leads to transformer heating and failure of the equipment. Voltage flicker are caused mainly due to sudden starting of motor, arc furnaces, rolling mills, switching of capacitor banks which affects seriously to the electronics instruments and reduces its life span. Single line to ground fault and unbalanced loading gives rise to voltage imbalance resulting in slowing down and heating of induction motor and also induces negative sequence current to compensator. Voltage sag are caused due to remote and parallel faults and due to starting of large scale generators and induction motor, whose undesirable consequence are equipment shutdown tripping of relays and capacitor banks, and malfunctioning of loads. Hence, genuine steps should be taken to maintain power system secured while improving the power transfer capability and also the reliability. UPQC is encouraging to attain the desired goals in maintaining the power quality[8,10], which is a combination of shunt and series devices namely D-STATCOM and DVR respectively. The ability of exchanging both real and reactive power makes UPQC a unique and effective custom power device, thereby enabling in enhancing the power quality.

Hence this paper suggests UPQC as a best custom power device to solve various power quality issues. Section 2 describes the UPQC and its control circuit. Various voltage sag indices calculation and CBEMA curve are described in section 3. Simulation results of two bus distribution system with and without UPQC under various fault conditions are described as section 4. Finally conclusion is reported in section 5.

2. Unified Power Quality Conditioner and Control Circuit

A schematic representation of UPQC shown in Figure 1, consists of series and shunt active filter connected back to back by a common dc link capacitor. All the current related problems such as power factor improvement, DC link voltage regulation, current harmonic compensation, reactive power compensation, load unbalance compensation etc are compensated by the shunt active filter. The series active filter is connected in series through a three phase transformer. All the voltage related problems such as voltage sag, swell, harmonics and flicker are compensated by series active filter and act as a controlled voltage source[11]. UPQC also have the capability to mitigate voltage unbalance, and can reduce real power loss. Based on the non linear load connected to the Point of Common Coupling(PCC), the voltage at PCC may be distorted or unbalanced[4]. Placement of UPQC in the distribution system plays a major role in mitigation of power quality issues.

Hence the scheme of series and shunt connected back to back active filters is the most sophisticated approach for mitigating all types of power quality problems.

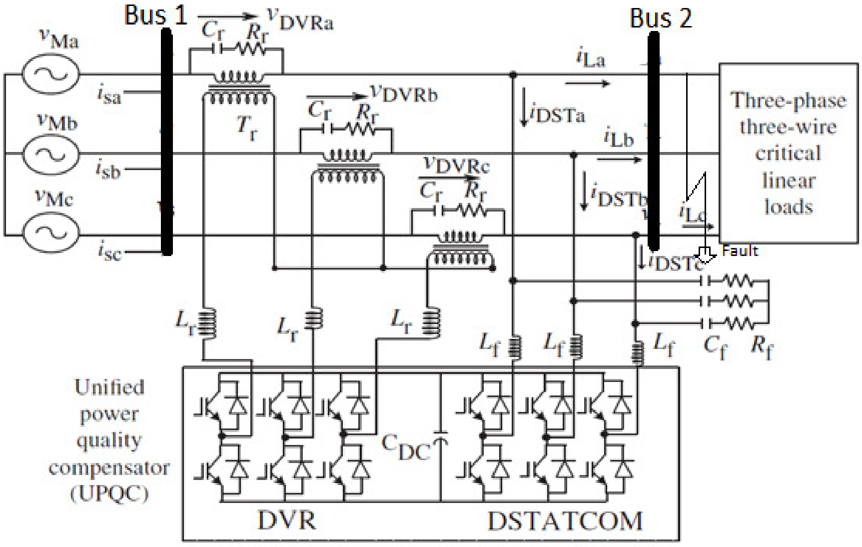


Figure 1. Schematic diagram of two bus distribution system with UPQC

For the control of DVR and DSTATCOM part of UPQC, there are many number of control algorithm used. The working of DSTATCOM in UPQC, synchronous reference frame theory(SRFT) based control algorithms is adopted in following sections [12].

The function of DSTATCOM is to improve the power quality of source current and also aid the common DC bus between DVR and DSTATCOM by absorbing active power at the time of transients. The block diagram of control scheme of DSTATCOM is depicted in Figure 2. The voltage at PCC (V_{SA}, V_{SB}, V_{SC}), the load currents (i_{LA}, i_{LB}, i_{LC}) and DC bus voltage are observed as feedback signal. The load current in abc frame are first transformed to the dqo frame as given below.

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \\ I_{L0} \end{bmatrix} = \left[\begin{pmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{2\pi}{3}) & \frac{1}{2} \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & \frac{1}{2} \end{pmatrix}\right] \begin{bmatrix} I_{la} \\ I_{lb} \\ I_{Lc} \end{bmatrix} \tag{1}$$

where, cos θ & sin θ are acquired with the help of three phase PLL using the PCC voltages. For producing the fundamental unit vectors, PLL signal is processed from PCC voltages, to convert sensed currents in dqo reference frame. Using the SRF controller, DC quantities are obtained with the help of LPF, hence the ripples are isolated from reference signal.

The direct and quadrature axis currents are given as

$$i_{Ld} = i_{dDC} + i_{dAC} \tag{2}$$

$$i_{Lq} = i_{qDC} + i_{qAC} \tag{3}$$

The output obtained from PI controller at the DC bus voltage of UPQC is contemplated as current (i_{loss})

$$i_{loss}(n) = i_{loss}(n-1) + K_{pd}\{v_{de}(n) - v_{de}(n-1)\} + K_{id}v_{de}(n) \tag{4}$$

where $V_{de}(n)$=V_{DC}-$V_{DC}(n)$ is the error between sensed (V_{DC}) and reference (V_{DC}) voltage at nth sampling time. K_{pd} and K_{id} are the proportional and integral gain constants of PI controller respectively.

Hence reference supply current amplitude is given as

$$i_d^* = i_{dDC} + i_{loss} \tag{5}$$

with the help of reverse park transformation iq and io are obtained as zero. Again using Reverse parks transformation, the resultant dqo currents obtained are again transformed into reference supply current.

$$\begin{bmatrix} I_{sa}^* \\ I_{sb}^* \\ I_{sc}^* \end{bmatrix} = \left[\begin{pmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{2\pi}{3}) & 1 \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & 1 \end{pmatrix}\right] \begin{bmatrix} I_d^* \\ I_q^* \\ I_0^* \end{bmatrix} \tag{6}$$

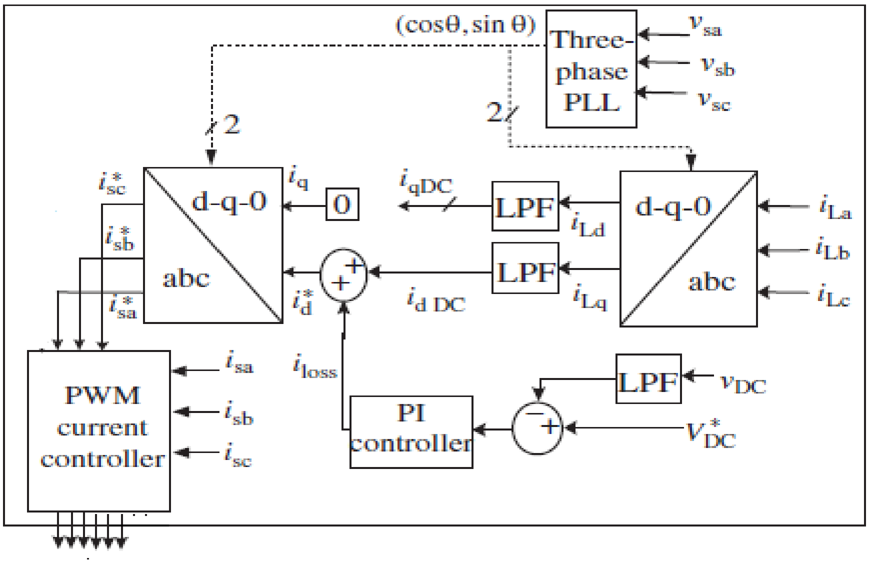


Figure 2. Control Algorithm for DSTATCOM portion of UPQC

Synchronous reference frame theory based control circuit is also adopted for DVR part of UPQC.[12]

3. **Voltage sag Indices**

The voltage sag indices such as Detroit Edison Sag Score, Voltage Sag Energy, voltage sag lost energy index(VSLEI), Phase Voltage Unbalance rate, and voltage sag severity are calculated based on the definition mentioned in references[13-21]. The values are tabulated in table 4and analysed in section 5. Fig.3 represents the Computer Business Equipment Manufacturer Associations (CBEMA) curve developed a standard to address energy performance profile for computer equipment and voltage sag severity algorithm is shown in Table -1.

Table 1: CBEMA voltage-sag severity algorithm

U_{curve}	Duration range (d)	Voltage Sag Severity (S_e) Calculation
0.0 pu	$d \le 20ms$	$S_e = \frac{(1-U)}{(1-0.0)}$ =1-U
0.7 pu	$20ms < d \le 500ms$	$S_e = \frac{(1-U)}{(1-0.7)}$ =3.3(1-U)
0.8 pu	$500ms < d \le 10s$	$S_e = \frac{(1-U)}{(1-0.8)}$ =5(1-U)
0.9 pu	$10s < d$	$S_e = \frac{(1-U)}{(1-0.9)}$ =10(1-U)

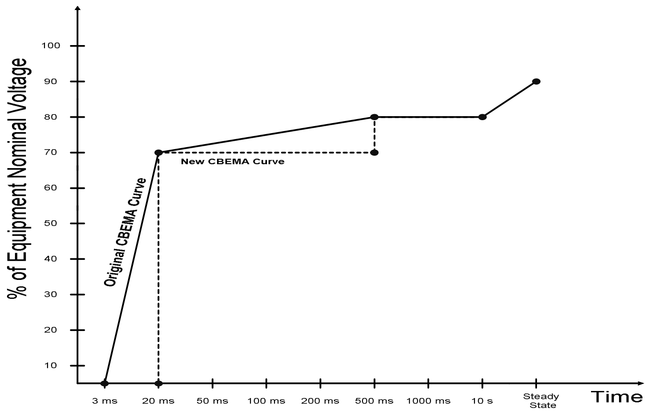


Fig. 3 Overlay of CBEMA curves

Table 2: Parameters of the two bus distribution system and UPQC

Parameter	Value
Supply Voltage (Peak to Peak)	415 V
Frequency	50 Hz
Line resistance	0.632 Ω
Line Inductance	4 mH
Injection transformer turns ratio	1:1
Series Injection transformer	25 KVA
Shunt Injection transformer	80 KVA
Switching Frequency	1 kHz
Load Real Power	20 KW
Load Inductive Reactive Power	100 VAR
Filter inductance	1 mH
Filter capacitance	10 μF
DC link capacitor	3000 μF

4. Simulation Results & Discussion

Two bus distribution system depicted in Fig-1 is simulated and various faults such as L-G, LL-G, LLL-G are incorporated near bus 2. The system parameter for Fig-1 is shown in table 2. Fault is created near bus 2 in Figure 1, between 0.2 to 0.3 seconds. UPQC operating under various fault conditions in distribution system are analyzed. Voltage sag, interruption, fault current, real power & reactive power are manifested in Table 3 & Figure 4-9.

From table 3 and Fig 4a, 6a & 8a results, it is observed that UPQC maintain the voltage profile (409V) under various fault conditions. Similarly from table 3 & Figure 4b- 9b, the current is maintained as 44A with UPQC under various fault conditions. Hence it is suggested that, UPQC is the best choice for both current & voltage related issues.

From table 3 and Figure 4c to 9c, the real power at buses without UPQC is increased in all the three cases under fault condition. After inserting UPQC the real power value is reduced to 24kW at bus 1 and 22 to 23 kW at bus 2. From table 3 and Figure 4d to 9d, without UPQC condition the reactive power is increased in both the buses and UPQC in all the three cases and it is reduced to 11 KVAR at bus 1 and 7.5 KVAR at bus 2. It is observed that the value of real and reactive power are exceeding the prefault value under all the three cases with UPQC.

Analysis of various system indices such as Sag Score, Voltage Sag Lost Energy Index, Voltage Sag Energy index, Voltage sag severity, & PVUR as manifested in table 4. Sag Score is calculated using equation 1 under various fault conditions, with and without UPQC results are compared. Without UPQC Sag Score values in all cases are greater than 6. With UPQC Sag Score values in all three cases is near to zero. If the Sag Score values are near to zero then the voltage profile is maintained in the three phase distribution systems. Voltage sag Energy is calculated using equation[13] under various fault conditions and values are compared with and without UPQC. Voltage sag lost Energy Index is calculated using equation[15] under various fault conditions. Voltage sag Severity is calculated using equation[15] under various fault conditions and in Figure 10, the values are plotted in CBEMA curve and results are compared with and without UPQC. Whereas with UPQC, all six values are within the reference curve hence there would not be any damage to the equipment.

THD analysis in distribution system under prefault, during fault and post fault conditions are analysed in table 5 and 6. The Voltage and current THD results are compared with and without UPQC. After insertion of UPQC all values of voltage and current THD are within the permissible limit to meet the IEEE standard 519-2014.

Also it is observed that the percentages of phase voltage unbalance rate are within the IEEE standard 112-1991 recommendations by insertion of UPQC.

Power factor is calculated at Bus 1 & Bus 2 as shown in Table 7. At the time of fault, without UPQC, the PF observed in three cases are 0.68, 0.56, and 0.50. After insertion of UPQC, the PF was raised to 0.90 in all three cases. At bus 2, without UPQC, the PF in three cases are 0.78, 0.81, and 0.54. With the installation of UPQC, the PF was maintained near to unity (0.95) in all three cases.

Table 3: Performance analysis of various system parameters

System Parameters		L-G	LL-G	LLL-G

		Pre-fault	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC
Bus 1	Voltage (Volts)	413	389	409	366	409	343	409
	Current(Amps)	44	113	44	186	44	261	44.5
Bus 2	Voltage (Volts)	380	253	362	127	362	0	362
	Current (Amps)	44	113	44	186	44	261	44
Bus 1	Real Power (KW)	27	48	24	60	24	70	24
	Reactive Power (KVAR)	3.815	51	11	88	11	120	11
Bus 2	Real Power (KW)	25	38	22	40	23	35	23
	Reactive Power (KVAR)	0.126	30	7.484	28	7.515	23	7.50

Table 4: Performance analysis of various indices at Bus 1 and Bus 2

		L-G		LL-G		LLL-G	
		With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC
Sag score (%)	Bus 1	0.0066	6.02	0.0066	11.56	0.0033	16.86
	Bus 2	0.0066	38.79	0.0066	69.39	0.0066	99.9
Voltage Sag Lost Energy Index		0.00049023	0.01845	0.000493472	0.2288	0.000497821	1.122
		0.012369	12.838	0.01883167	63.55	0.01918023	299.45
Voltage sag Energy Index(E_{VS})		0.0117	1.08	0.00879	2.10	0.008309	3.022
		0.01157	6.25	0.01928	9.06	0.001103	9.99
Voltage Sag severity		0.033	0.231	0.033	0.39	0.033	0.561
		0.033	1.28	0.033	2.27	0.033	3.29
PVUR (%)		0.0586	5.57	0.043	11.14	0.041	16.46
		0.043	33.16	0.093	66.58	0.0055	99.9

Table 5: Performance Analysis of Bus 1 & Bus 2 THD in Distribution System

%THD	Pre Fault		During Fault					
			L-G		LL-G		LLL-G	
	With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC
V_{THDa1}	0.20	4.88	0.02	2.00	0.03	2.00	0.02	2.00
V_{THDb1}	0.22	4.70	0.02	6.14	0.02	2.25	0.03	2.25
V_{THDc1}	0.26	4.61	0.03	6.31	0.03	1.79	0.03	3.59
I_{THDa1}	1.04	14.74	0.13	19.65	0.14	19.65	0.13	19.64

I_{THDb1}	1.15	14.50	0.10	11.80	0.12	5.55	0.13	5.56
I_{THDc1}	1.38	14.70	0.13	10.98	0.13	9.78	0.17	16.69
V_{THDa2}	1.16	29.24	0.13	459.30	0.14	464.84	0.14	471.72
V_{THDb2}	1.26	28.24	0.11	33.21	0.14	477.44	0.15	486.94
V_{THDc2}	1.50	27.69	0.15	39.92	0.15	9.24	0.16	479.42
I_{THDa2}	1.04	14.74	0.13	19.65	0.14	19.65	0.13	19.64
I_{THDb2}	1.15	14.50	0.10	11.80	0.12	5.55	0.13	5.56
I_{THDc2}	1.04	14.70	0.13	10.98	0.15	9.78	0.17	16.69

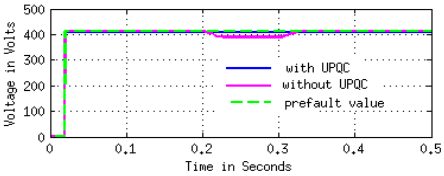
Table 6: THD Analysis in Distribution System after Clearing Fault

%THD	After Clearing Fault					
	L-G		LL-G		LLL-G	
	With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC
V_{THDa1}	0.01	10.74	0.28	11.06	0.31	5.26
V_{THDb1}	0.01	10.62	0.28	10.97	0.31	5.05
V_{THDc1}	0.01	10.61	0.28	10.92	0.31	5.05
I_{THDa1}	0.0	14.75	0.0	14.70	0.0	14.77
I_{THDb1}	0.0	14.52	0.0	14.53	0.0	14.58
I_{THDc1}	0.0	14.72	0.0	14.69	0.0	14.75
V_{THDa2}	0.04	64.31	1.59	66.22	1.72	31.56
V_{THDb2}	0.03	63.34	1.59	65.76	1.72	30.33
V_{THDc2}	0.04	63.55	1.59	65.41	1.72	30.31
I_{THDa2}	0.0	14.75	0.0	14.70	0.0	14.77
I_{THDb2}	0.0	14.52	0.0	14.53	0.0	14.58
I_{THDc2}	0.0	14.72	0.0	14.69	0.0	14.75

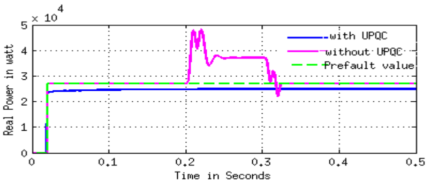
Table 7 Power Factor calculation at Bus 1 & Bus 2 (with RL Load)

BUS	L-G		LL-G		LLL-G	
	With UPQC	Without UPQC	With UPQC	Without UPQC	With UPQC	Without UPQC
Bus 1	0.90	0.68	0.90	0.56	0.90	0.50
Bus 2	0.94	0.78	0.95	0.81	0.95	0.54

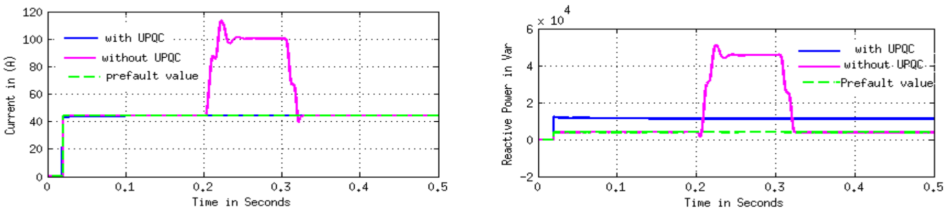
Simulation Results :



(a)

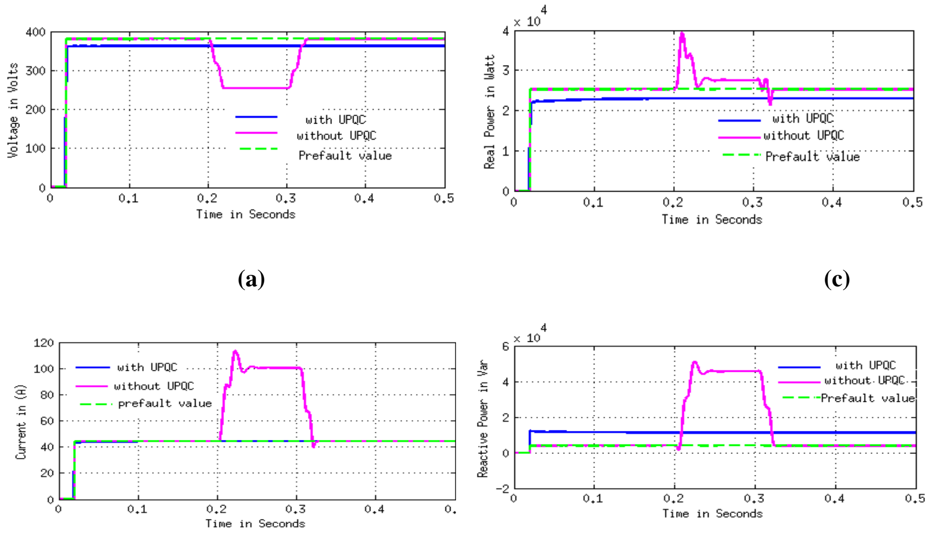


(c)



(b) **(d)**

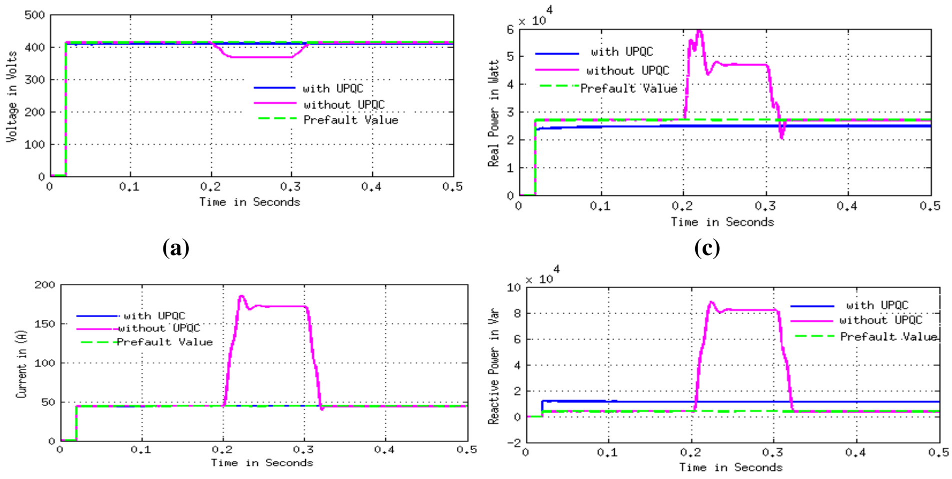
Figure 4. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Single Line to Ground fault at Bus 1



(a) **(c)**

(b) **(d)**

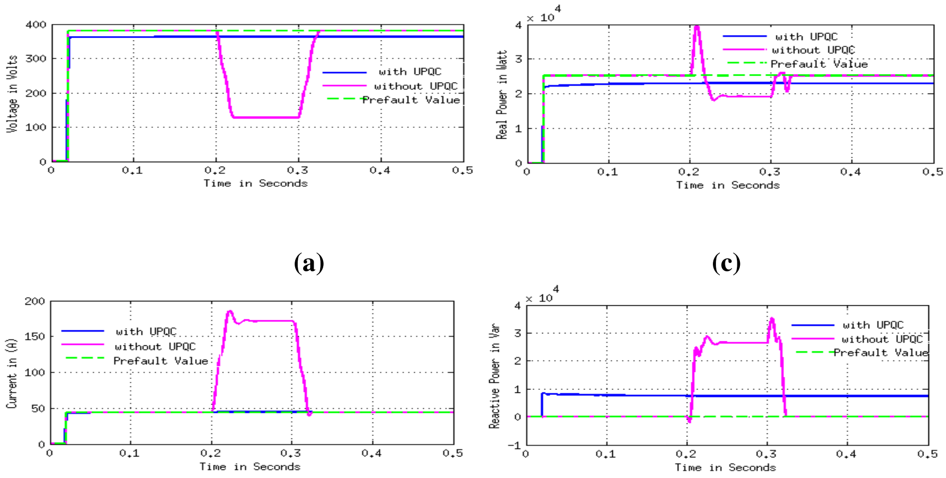
Figure 5. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Single Line to Ground fault at Bus 2



(a) **(c)**

(b) **(d)**

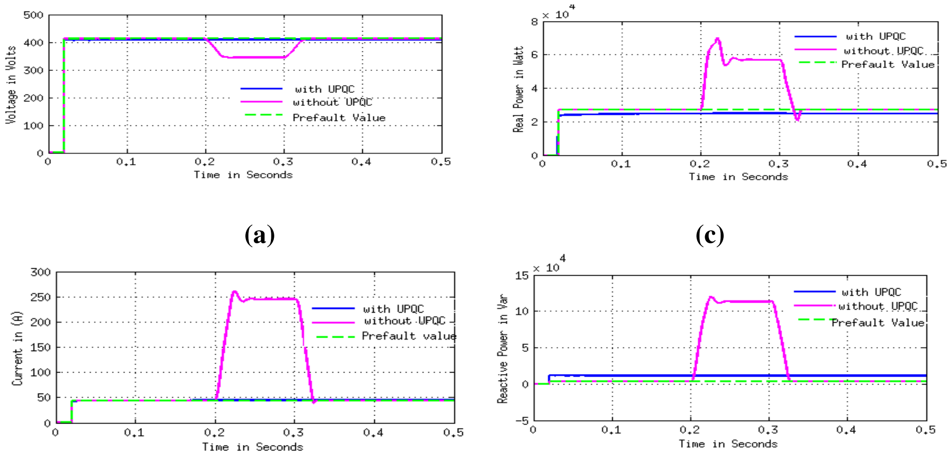
Figure 6. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Double Line to Ground fault at Bus 1



(a) **(c)**

(b) (d)

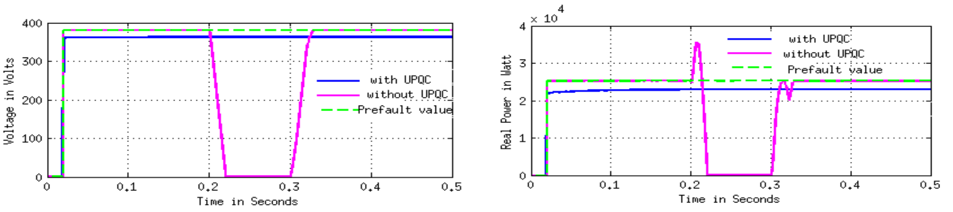
Figure 7. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Double line to Ground fault at Bus 2



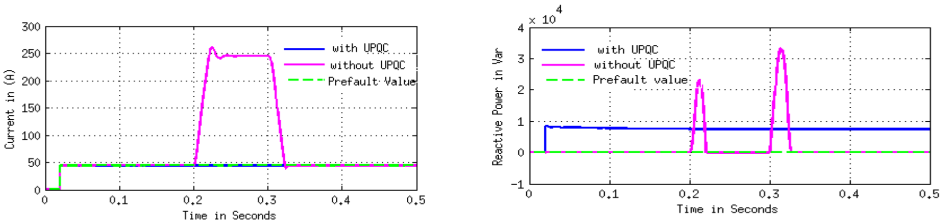
(a) **(c)**

(b) **(d)**

Figure 8. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Three Phase to Ground fault at Bus 1



(a) **(c)**



(b) **(d)**

Figure 9. a) Voltage, b) Current, c) Real Power, d) Reactive Power during Three Phase to Ground fault at Bus 2

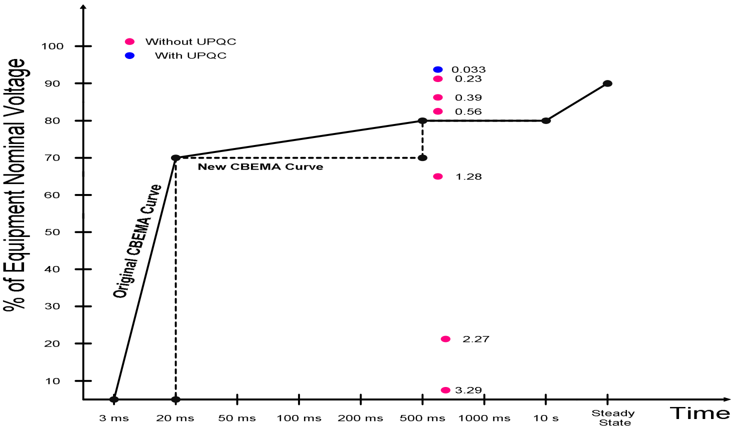


Figure 10. CBEMA Curve Voltage Sag Severity

5. Conclusion

Identification of sag, swell and harmonics in voltage and current waveform is the main step to solve various problems occurring in electrical power distribution system. In this paper, the performance of UPQC is analyzed under different fault conditions such as symmetrical and unsymmetrical faults. THD analysis is done for both voltage and current and the results are within prescribed limits as per IEEE519-2014. Also, brief analysis on system indices is done. The closed loop simulation of UPQC is done using PI controller in the MATLAB/SIMULINK environment. The simulation result clearly states that UPQC compensated the voltage and current harmonics, voltage sag/swell and suppressed the fault current. The real and reactive power were also near to the prefault values after insertion of DVR. Also, power factor is maintained to unity after installation of UPQC during fault condition. Hence UPQC gives one shot compensation for almost all the power quality related issues present in the electrical power systems.

References

[1] M. Hosseini, H.A. Shayanfar, M. Fotuhi-Firuzabad "Modeling of unified power quality conditioner (UPQC) in distribution systems load flow" Energy Conversion and Management 50 (2009) 1578-1585.

[2] Ali Mahmoudian, Mohsen Niasati, Mojtaba Ahmadieh Khanesar, "Multi objective optimal allocation of fault current limiters in power system" Electrical Power and Energy systems 85(2017), 1-11.

[3] Sai Shankar, Ashwani Kumar, "Operation of Unified power quality conditioners under Different situations" IEEE Power and Energy Society General Meeting, Pages: 1 - 10, 2011.

[4] Ahmed M.A. Haidar, Chellali Benachaiba, Faisal A.F. Ibrahim, Kamarul Hawari, "Parameter Evaluation of Unified Power Quality Conditioner" Electro/Information Technology (EIT), IEEE International Conference on 15-17 May 2011

[5] G.J. Li, F.Ma, S.S choi, X.P.Zhang "Control strategy of a cross-phase-connected unified power quality conditioner" IET Power Electron, Vol. 5, Issues 5, pp. 600-608, 2012.

[6] Ali sahebi, Haidar Samet, Teymoor Ghanbari, "Evaluation of power transformer inrush currents and internal faults discrimination methods in presence of fault current limiter" Renewable and sustainable Energy Reviews vol.68, pp. 102-112, 2017.

[7] Georgi Ganev, Krastjo Hinov, Nikolay karadzhov, "Fault current limiters - Principles and Application"

[8] D.V.N. ananth, G.V. Nagesh Kumar, "Mitigation of voltage dip and power system oscillations damping using dual STATCM for grid connected DFIG" Ain Shams Engineering Journal, 2015.

[9] Andrea Staino, Biswajit Basu, Malabika Basu "Suppression of Grid Fault-induced Vibration in wind Turbines using UPQC" Power Electronics for Distributed Generation Systems (PEDG), 2014 IEEE 5th International Symposium on 18 August 2014.

[10] L.Xu,L. Yao and C. Sasse, "Comparison of using SVC and STATCOM for wind farm integration", in power system technology 2006, Powercom 2006, International conference on pp. 17.

[11] Jayanti Sarker, S.K. Goswami, "Optimal Location of Unified Power Quality Conditioner in Distribution system for Power Quality Improvement" Electrical Power and Energy Systems Vol.83 pp. 309-324, 2016

[12] Ambrish Chandra, Bhim Singh, and Kamal Al-Haddad "Power Quality: Problems and Mitigation Techniques" *Wiley publisher,* ISBN: 978-1-118-92205-7, Dec 2014

[13] R. S. Thallam and G. T. Heydt, "Power acceptability and voltage sag indices in thethree phase sense," Panel Session on Power Quality - Voltage Sag Indices, *IEEE Power Engineering Society Summer Meeting, Seattle*, 2000.

[14] Arindam Ghost, Gerard Ledwich, "Power Quality Enhancement Using Custom Power Devices" *Kluwer's Acadamic Publisher*

[15] M. H. J. Bollen, "Voltage sag indices - Draft 1.1", with contribution from D. Sabin, IEEE Panel on Voltage Sag Indices, August 2, 2000.

[16] M.H.J. Bollen; D.D. Sabin; R.S. Thallam Voltage sag indices – draft 5. Technical report working document for IEEE P1564, November 2003.

[17] Pierluigi Caramia, Guido Carpinelli, Paola Verde, "Power Quality Indices in Liberalized markets" *Wiley Publishers.*

[18] http://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/power quality/voltage_tolerance.pdf

[19] Ambrish Chandra, Bhim Singh, and Kamal Al-Haddad "Power Quality: Problems and Mitigation Techniques" *Wiley publisher,* ISBN: 978-1-118-92205-7, Dec 2014.

[20] IEEE standard 112-1991. IEEE standard test procedure for polyphase induction motors and generators:1991.

[21] Ahmed M. Saeed a , Shady H.E. Abdel Aleem Murat E. Balci c , Essam E.A. El- Zahab a, Ahmed M. Ibrahim a,"Power conditioning using dynamic voltage restorers under different voltage sag types" *Journal of Advanced Research* Vol.7, pp.95–103, 2016.