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Universal Power Line Manager for Distributed Generation

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Abstract: The study proposes a new power line conditioner called universal power line manager. The power circuit of a general Universal Power Line Manager (UPLM) is based on the combination of UPQC, UPFC and frequency changer (Matrix converter). This equipment incorporates compensation functions like voltage sag, voltage swell, reactive power compensation, current harmonic rejection, real power flow control, damping the system and also provides frequency regulation. Integrated series and parallel active filter (UPQC) is a universal solution for the most power quality problems in distribution systems and the integrated series and shunt active converter (UPFC) compensates the reactive power and power flow control in distributed system. The matrix converter is used for the frequency regulation. For these integration, the compensator proposed in this study will be called as the Universal Power Line Manager (UPLM). Simulation results are presented to confirm that the new approach has better performance over the existing power quality conditioners.

Key words: UPQC, UPFC, matrix converter, UPLC, frequency changer, India

INTRODUCTION

A universal active power line conditioner is an advanced concept in the power quality control field. The universal active power line conditioner is implemented based on the idea of integration of unified power quality conditioner and unified power flow conditioner that shares a single DC link (Aredes *et al*., 1998). Universal active power line conditioner can be applied in a power system for current harmonic compensation, voltage compensation, reactive power control, enhanced power flow control (Aredes and Heumann, 1996). The Pulse Width Modulation technique (PWM) is commonly used to control all these converters. The switching rate is high so the PWM converter can produce controlled current or voltage waveform with high fidelity.

Depending upon the controller and filter arrangement, these converters can characterize into different compensation functions. The series and shunt active converters are combined together and it acts as an active filter, this arrangement is called as unified power quality conditioner (Khadkikar *et al*., 2006). It can simultaneously compensates the load current harmonics and supply voltage harmonics. In the modification of the control system of series and shunt active converter can simultaneously compensates power flow control and voltage regulation. This modification is called as unified power flow conditioner (Sharma and Jagtap, 2010). These two controllers (UPQC and UPFC) are combined together that arrangement is called as Universal Power Line Conditioner (UPLC). There is a drawback in the UPLC, i.e., universal power line conditioner cannot compensates or regulates power frequency variation. Because, there is no device present to control the supply frequency. The power frequency variation is an important power quality issue in the distribution system (Divya and Rao, 2008). If the supply frequency varies beyond the power quality, the utility equipment may not work properly (Enguo *et al*., 2008). A new power line conditioner proposed in this study is intended to be installed at the Point of Common Coupling (PCC) in a power system. This power line conditioner is called as Universal Power Line Manager (UPLM). It is a combination of Unified Power Quality Conditioner (UPQC), Unified Power Flow Conditioner (UPFC) and frequency regulator (Matrix converter). Figure 1 shows an arrangement of universal power line manager. The proposed universal power line manager can

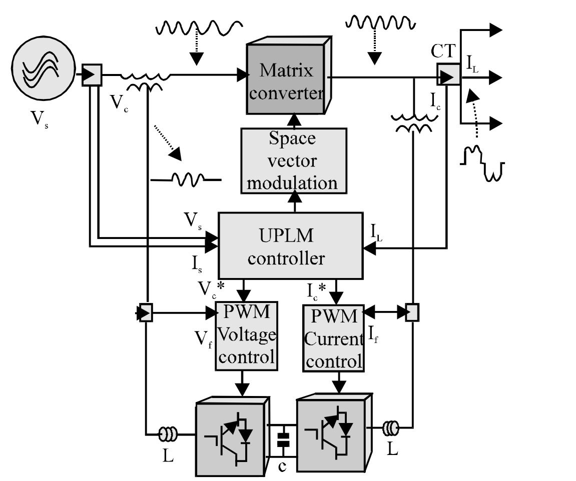

Fig. 1: Basic configuration of universal power line manager

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solve all power quality issues like voltage sag, voltage swell and eliminates current harmonics (by using UPQC control), power flow and voltage regulation (by using UPFC part) and frequency regulation (by using matrix converter part). Matrix converter has so many advantages when compared to traditional frequency changers. Matrix converters can convert the supply frequency in wide range (Haruna and Itoh, 2008). It can also compensate the voltage sag and swell efficiently by adjusting the modulations (Kang *et al.*, 2002). In Matrix Converter (MC), it is possible to control the phase angle between the voltages and current on the output (Nikkhajoei and Iravani, 2006).

Size, high power density and easier maintenance are the attractive characteristics of matrix converter. Sinusoidal input current, controlled input power factor, regeneration capability and magnitude-frequency controllable of output voltages are the advantages of matrix converter.

SYSTEM CONFIGURATION OF UNIVERSAL POWER LINE MANAGER

Construction: The basic components of the UPLM is the Voltage Source Inverter (VSI's) sharing a common DC storage capacitor and a matrix converter connected to the power system through coupling transformers. One VSI is connected in shunt to the transmission line via a shunt transformer while the other one is connected in series through a series transformer.

The series converter is connected in series with the supply through a transformer (T_1-T_3) while shunt converter is connected in parallel with the passive filter ($L_{P(1-3)}$ $R_{P(1-3)}$) and ($R_{P(1-3)}$ $C_{P(1-3)}$). The passive filters are used to minimize the switching oscillation in the converter output. Each converter and filter consists of three single phase voltage-source PWM inverters using power IGBTs. The shunt converter compensates the reactive power, voltage stability, current harmonic rejection.

The series converter controls the power flow to the utility, voltage regulation and voltage harmonic rejection. The dc terminals of the inverters are connected to each other and a dc capacitor of 2200 pF is connected in parallel. The matrix converter is used to regulate the load frequency. A harmonic-sensitive load L_1 (Induction motor) and harmonic-producing load L_2 (Rectifier load) are connected to the common bus where the bus voltage $V_{s(a-c)}$ is 440 V.

A three-phase twelve-pulse thyristor based rectifier of 20 kVA is an identifying harmonic load which dominantly produces 7 and 11th harmonic currents. A power capacitor of 5 kVA with a series reactor of 5% of the capacitor rating is considered as a hypothetical harmonic-sensitive load because voltage distortion at the common bus causes a large amount of harmonic currents flowing through the load. A detailed UPLM construction scheme is shown in Fig. 2. The main circuit of the Universal Power Line Manager (UPLM) consists of matrix converter placed in between the series converter and shunt converter arranged as per the circuit diagram. This type of arrangement is called as tandem based converter. This type of arrangement can avoid the limitations of matrix converter (Jenopaul *et al.*, 2011).

The matrix converter consists of a single-stage converter which has an array of m x n (3×3) bi-directional power switches to link. It consists of nine bi-directional switches arranged in three groups each being associated with an output line. This bi-directional switches arrangement connects any of the input lines to any of the output lines. Commonly, the matrix converter can convert the input frequency to the output. In this study, the power rating of matrix converter is 120 kVA and the input voltage of 440 V three phase and the frequency of output 60 Hz regulated.

Matrix converter working principle: A matrix with elements S_{ij} represents the state of each bi-directional switch (on = 1, off = 0) can be used to represent the matrix output voltages (V_u-V_w) as functions of the input voltages (V_a-V_c) as follows:

$$\begin{bmatrix} V_u \\ V_v \\ V_w \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

The input phase currents (i_a-i_c) are related to the output phase currents (i_u-i_w) by:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{31} & S_{23} & S_{33} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (2)$$

Assume that the input voltages of the converter system of balanced sinusoidal waveforms as:

$$\begin{bmatrix} V_{ia}(t) \\ V_{ib}(t) \\ V_{ic}(t) \end{bmatrix} = \begin{bmatrix} V_i^m \sin(\omega_i^t) \\ V_i^m \sin(\omega_i^t - \frac{2\pi}{3}) \\ V_i^m \sin(\omega_i^t - \frac{4\pi}{3}) \end{bmatrix} \quad (3)$$

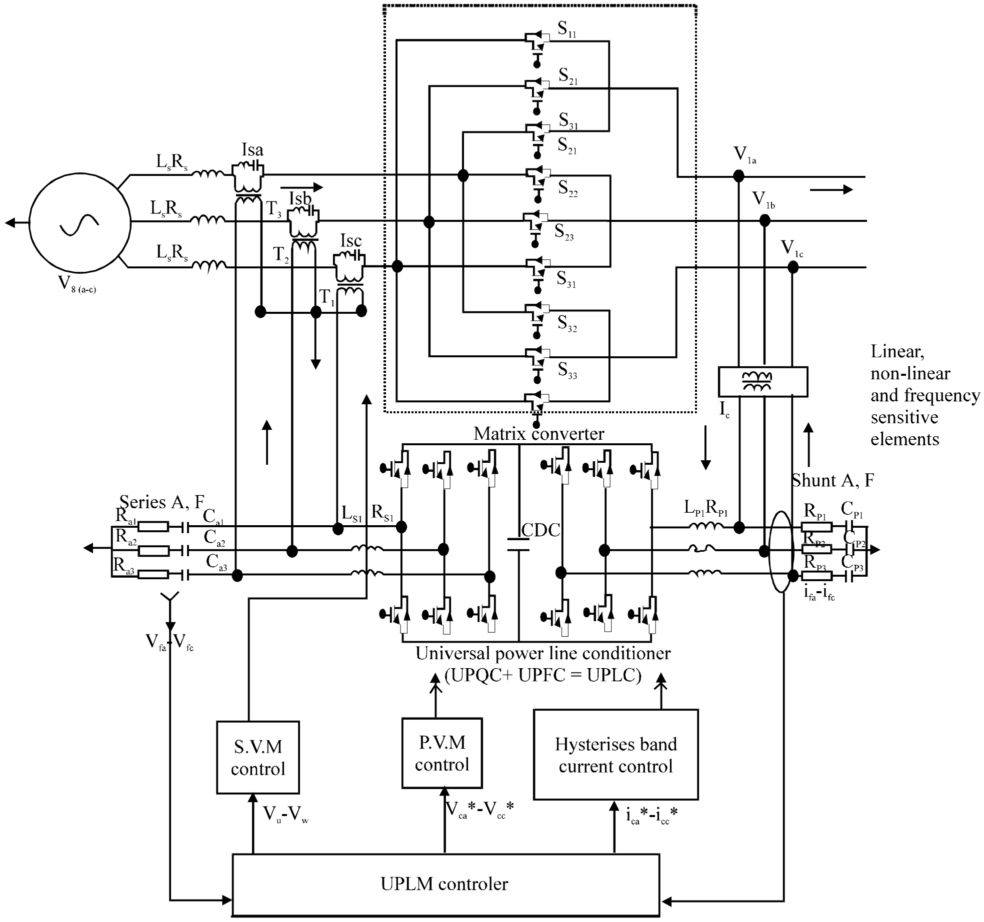

Fig. 2: The proposed universal power line manager

Where:

V_i^m = The amplitude of the input voltages

ω_i = The angular frequency of the input voltages

The output voltages are desired to be balanced sinusoidal waveforms. Consider a desired output phase of voltage as:

$$V_{oa}(t) = V_o^m \sin(\omega_o^t + \delta) \quad (4)$$

Where:

V_o^m = The amplitude of the converter output voltage

ω_o = The angular frequency of the converter output voltage

CONTROL SCHEMES OF UNIVERSAL POWER LINE MANAGER

The control system of Universal power line manager consists of three sections:

Frequency regulating control block: The control diagram of the matrix converter based frequency regulated power supply for utility is shown in Fig. 3. Conventional space vector pulse width modulation strategy can be used for

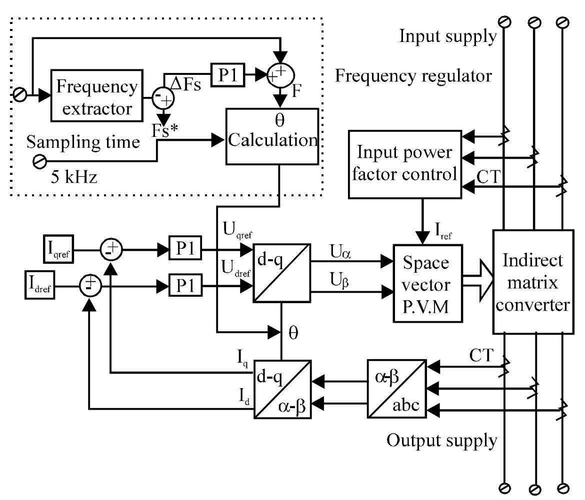

Fig. 3: Control system of frequency regulator in matrix converter

matrix converter. The principle of this control method is similar as the flux oriented vector control technique of AC motor drives while the speed control loop is omitted and the coordinate transformation angle (θ) is calculated according to the output frequency (f) and the sampling time (t). The supply frequency, f_s is compared with the reference frequency f_s*. The frequency error signal Δf_s is applied to a frequency regulator/controller. Usually, the PI (proportional-integral) type controller which generates the reference frequency, f_{ref}. When f_{ref} is added to f_s, the required supply frequency f_{ref}* is obtained. The reference output voltage vector (represented by U_α, U_β) is provided by the output current controller and the reference input current vector (I_{ref}) is determined by the input voltages and input displacement angle θ through the input power factor control. The detailed modulation process is presented by Chen *et al*. (2011). The output currents have been transformed into d-q reference frame. The magnitude of output current can be controlled through by setting the values of i_{dref}, i_{qref}. When the above values are fed to the voltage controller (d-q), the phase voltage U_u-U_w will be get. After the anti-transformed phase voltage (U_u-U_w), the coordinate systems are obtained. Depending upon the control signal, the space vector modulator produces corresponding Pulse Width Modulation (PWM) signal to the matrix converter.

Shunt part control system of UPLM: The proposed model's shunt power converter control is shown in Fig. 4. The shunt part of the UPLM control system having the combination of shunt active filter and STATCOM controller characteristic.

Instantaneous reactive power (p-q) theory is used to control the shunt active power converter. Initially, the instantaneous three-phase load current and reference voltages are transformed as α-β-0 from a-b-c coordinates using (Eq. 5 and 6):

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

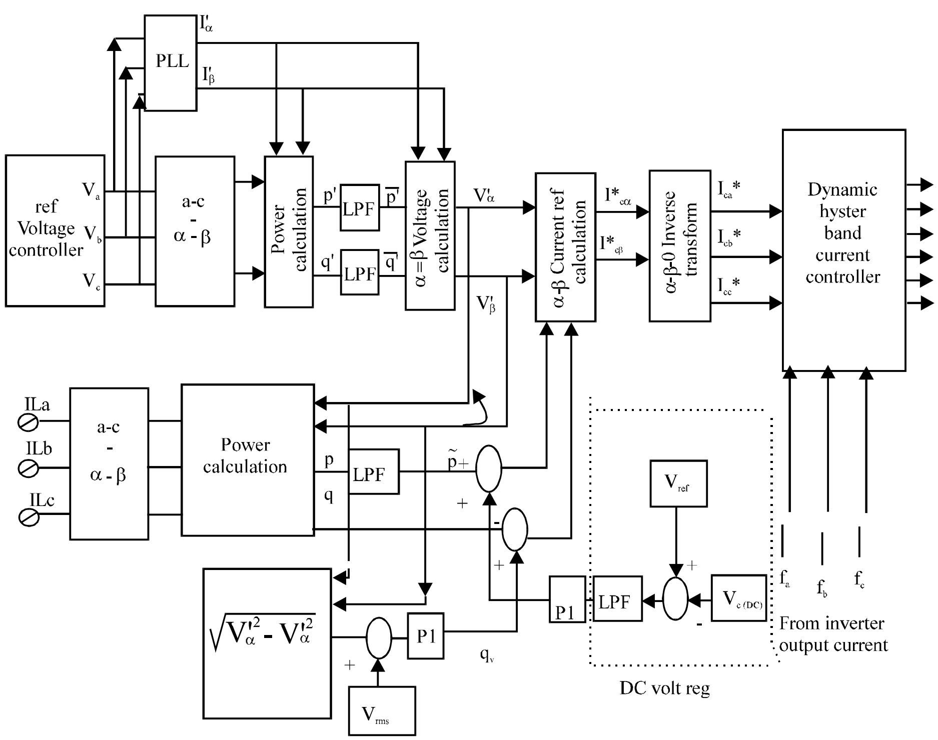

Fig. 4: Control system of shunt converter in UPLM

The reference α-β voltages and currents are converted into the p′-q′ and p-q using the relation (Eq. 7):

$$p = v'_{\alpha} i_{1\alpha} + v'_{\beta} i_{1\beta},\ q = v'_{\alpha} i_{1\beta} - v'_{\beta} i_{1\alpha} \tag{7}$$

where, p and q are the real and reactive power. Thus, the instantaneous values of the positive sequence voltage can be calculated as:

$$\begin{bmatrix} v'_{\alpha} \\ v'_{\beta} \end{bmatrix} = \frac{1}{i_{\alpha}'^{2} + i_{\beta}'^{2}} \begin{bmatrix} i'_{\alpha} & i'_{\beta} \\ i'_{\beta} & -i'_{\beta} \end{bmatrix} \begin{bmatrix} \bar{p}' \\ \bar{q}' \end{bmatrix} \tag{8}$$

v_{α}' and v_{β}' are the positive sequence reference instantaneous voltages I_p and I_q are the positive sequence real and reactive power. The real and reactive power consists of two average powers:

$$\text{Real power}(p) = \bar{p} + \tilde{p} \tag{9}$$

$$\text{Reactive power}(q) = \bar{q} + \tilde{q} \tag{10}$$

Where:

$\bar{p}, \bar{q}$ = Average powers
$\tilde{q}, \tilde{p}$ = Oscillating powers

The two fifth order butter worth filter is used to obtain the average power ($\bar{p}'$) and ($\bar{q}'$). PLL tracks continuously the fundamental frequency of the measured system voltages. The phase locked loop is used to operate properly under distorted and unbalanced voltage waveforms. The PLL generates Iα (sin θ) and Iβ (cos θ) to the DC power. The $\bar{p}$ loss must be always present to compensate the losses in the UPLM and to neutralize dc voltage variations caused by the series converter. The DC power loss compensation controller made up of PI controller efficiently compensates the power loss present in the DC capacitor voltage. The load voltage $V_{L(a-c)}$ can be regulated by the shunt active converter of the UPLM. The regulation of voltage $V_{L(a-c)}$ is achieved by a reactive current component $I_{c(abc)}$ injected which is orthogonal. So, the voltage across L_{p1} and R_{p1} is either in phase or in counter phase to $V_{L(sbc)}$. A reference value V_{rms} for the desired amplitude of the fundamental components of voltage is locally fixed (reference) and it is compared with the calculated values of instantaneous. The error signal passes through a PI controller that ($\bar{q}_v$) determines the necessary generation of imaginary power to regulate the voltage. The instantaneous aggregate rms line voltage is calculated as:

$$V_{rms} = \sqrt{v_{\alpha}'^{2} + v_{\beta}'^{2}} \tag{11}$$

The output $\bar{q}_v$ can be added to the compensating imaginary power q of the load. To protect the shunt converter against overload limiters have been implemented in front of PI controller. The current references are found to be:

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{v_{\alpha}'^{2} + v_{\beta}'^{2}} \begin{bmatrix} v'_{\alpha} & -v'_{\beta} \\ v'_{\beta} & v'_{\alpha} \end{bmatrix} \begin{bmatrix} -\tilde{\tilde{p}} & \bar{p}_{loss} \\ -q & \bar{q}_v \end{bmatrix} \tag{12}$$

The current references $i_{c\alpha}^*$ and $i_{c\beta}^*$ compensates the unbalanced voltage due to the fundamental negative sequence components and all harmonics current (i_{ca}-i_{cc}) tracks strictly by their reference (i^*_{ca}-i^*_{cc}), respectively. The switching signals are used in shunt active power filter control algorithm which is generated by comparing reference currents and actual line currents using hysteresis band current control algorithm. Hysteresis-band control results in a reduced ripple and lower harmonic content.

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} \tag{13}$$

The reference currents in the three-phase system (i^*_{ca}-i^*_{cc}) are calculated in order to compensate harmonic and reactive currents in the load. Due to the switching of converter, the currents i_{fa}-i_{fc} have some unwanted harmonics that can be easily filtered using small passive filter represented by R_{p123}, C_{p123} and R_s. If the filtering is ideal then the compensating current (i_{ca}-i_{cc}) tracks strictly by their reference (i_{ca}^*-i_{cc}^*), respectively. The switching signals are used in shunt active power filter control algorithm which is generated by comparing reference currents and actual line currents using hysteresis band current control algorithm. Hysteresis-band control results in a reduced ripple and lower harmonic content.

Series part control system of UPLM: The proposed series active control system is shown in Fig. 5. The control algorithm includes the combination of series active filter and SSSC control, i.e., the control system is designed to control the unbalance voltage compensation, voltage harmonic minimization, real and reactive power control. Real power control is for desired load condition in which the current can be controlled. The desired load condition is called as the power order. Power order is categorized by real power order p_{ref} and imaginary power order q_{ref}. The series converter components in the series voltage controller sense the resonance effect and residual harmonics current. These harmonic current oscillates the real and imaginary power (p_h and q_h) which is separated

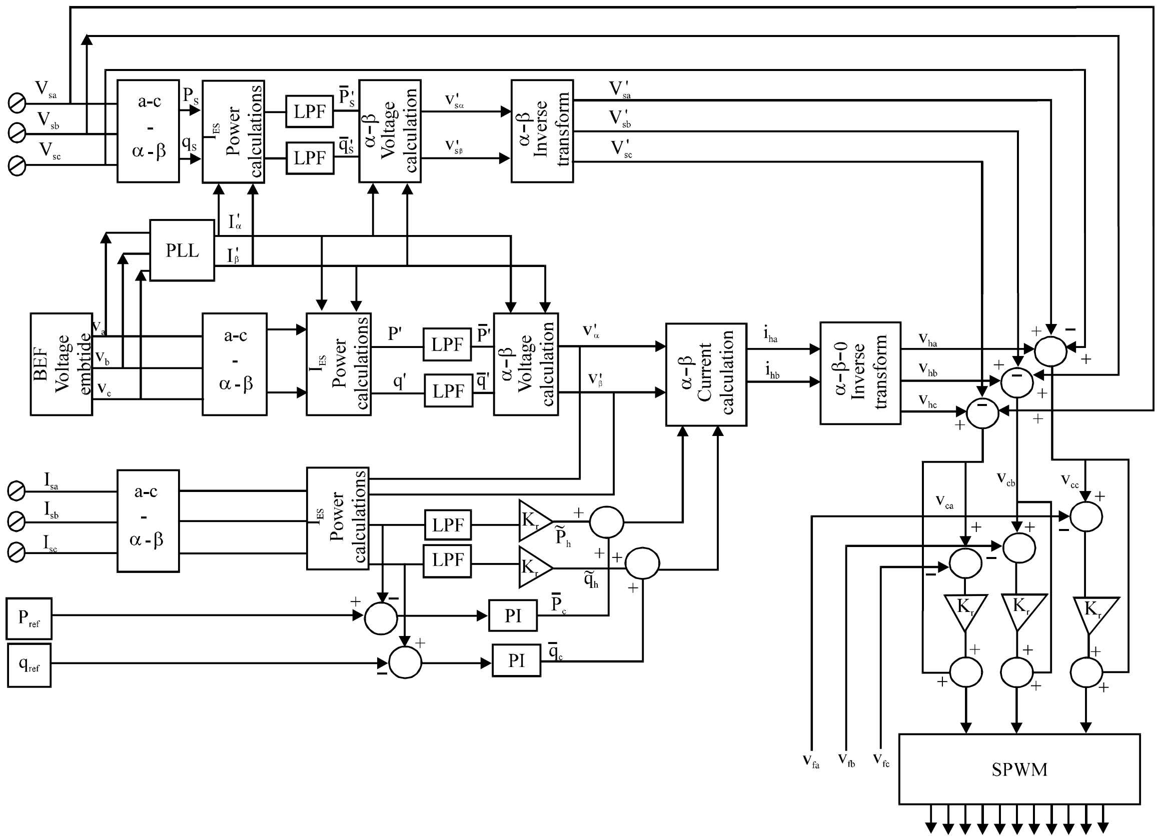

Fig. 5: Control system of series converter in UPLM

by high pass filter. The voltage reference (V_{cc}^*, V_{cb}^*, V_{ca}^*) makes the series converter as a harmonic isloater and improves the system stablity. It makes the series converter behaves as a series resistance for harmonic currents. Power flow control is included in the control circuit through positive average real power (P_c) and positive average imaginary power (q_c). In steady state, there is no error between the power orders p_{ref} and q_{ref} and the average values of the instantanous powers, p_h and q_h which are calculated from $V_{(abc)}$ and $I_{s(abc)}$. By inserting a fundamental voltage component $V_{c(abc)}$ through the series converter, it can change the phase angle and the amplitude of the voltage. So, the current flowing in the controlled distributed line changes to match the power orders p_{ref} and q_{ref}. To protect the series converter against overload, limiters have been implemented in front of PI controller. In addition, PLL conversion is used for reference voltage calculation. It represents a compensating component that includes all portions of the voltage V_S that are different from the fundamental positive sequence voltage component. Additionally, the signal zero sequence harmonic current (I_{ho}) provides harmonic isolation and damping for zero sequence currents flowing through the series converter. For the rest of harmonic components, the damping and harmonic isolation are made by the signals $\tilde{p}_h$ and $\tilde{q}_h$. $I_{h\alpha}$ and $I_{h\beta}$ are calculated by the α-β current references. α-β conversion is already discussed in the previous chapter.

Actually, these control signals are passed through an α-β-0 inverse transformation and get instantaneous voltage references (V_{ha}-V_{hc}). Variation in the power angle δ (phase angle) is the displacement between the voltages at both ends of a grid line which affects the active power flow more than the reactive power. For this purpose, a signal $\bar{q}_c$ is provided which makes the series converter to insert a fundamental voltage component orthogonal to the voltage $V_{L(abc)}$ (right side of the UPLC). On the other hand, a variation in the amplitude of the voltage affects strongly the reactive power of the system. Thus, a signal $\bar{P}_c$ is provided which generates a compensating component is in-phase with $V_{s(abc)}$. Due to the switching of converter, the voltages V_{fa}-V_{fc} have some unwanted high order harmonics that can be easily filtered using small passive filter represented by R_{s123}, Cs_{123} and L_{s123}. If the filtering is ideal then the compensating current (V_{ca}-V_{cc}) tracks strictly by their reference (V_{ca}^*-V_{cc}^*), respectively. The switching signals are used in series active power converter control algorithm is generated by comparing reference voltages and actual line voltages. Sine PWM control is used for the series converter. Functions of Universal Power Line Manager (UPLM) are:

- Compensate voltage harmonics
- Improve system stability (damping)
- Control the active and reactive power flow
- Compensate current harmonics
- Regulate the supply frequency to load
- Regulate the terminal voltage of power line

SIMULATION RESULT

To validate the effectiveness of the proposed system different cases have been examined for this study. In the proposed circuit simulations are carried out using Matlab/Simulink for voltage sag, current harmonics, reactive power control, real power flow control and frequency regulation investigations. Results of each test are described as:

Voltage sag: In Fig. 6, the UPLM compensates the sag and swell voltage effectively as shown in the simulation result. After implementing UPLM, the sag is compensated from 0.1-0.25 sec and the swell is compensated from 0.25-0.4 sec.

Current harmonics: The current harmonics are produced by the supply current is affected by the harmonic loads. Normally, the harmonic loads are rectifier based loads like the variable speed drives. In this simulation, the diode based rectifier load is analyzed and the power rating of the load is 30 kW.

The load is used to get the non-sinusoidal current from the power supply. Figure 7 shows after the implementation of UPLM, the current goes to sinusoidal. It effectively compensates the current harmonics. The simulation result shows the single phase only. The total current is 30 kVA. The simulation is carried out for a period of 0.15-0.45 sec.

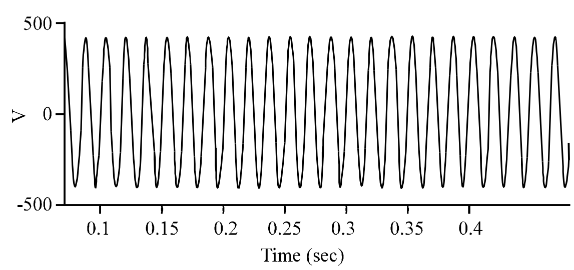

Fig. 6: UPLM based compensated load voltage

Reactive and real power control: The total real and reactive powers were drawn from the three-phase supply without the control of the UPLM. The total real power is 190 kVar and the reactive power is 85 kVar. In Fig. 8, the real power flow is controlled by the UPLM . The real power P_{ref} is set as 175 kVA, i.e., the power flow is set to the load as 175 kVA up to 0.25 sec. After that the P_{ref} is changed as 200 kVA. The UPLM control system controls the power flow as per the P_{ref}. At 0.25 sec, the power flow is controlled efficiently by the UPLM as shown in the Fig. 8. Reference P_{ref} is also simulated in the same simulation. Figure 9 shows the reactive power flow control by the UPLM. In this the q_{ref} is set by two values. Initially, the q_{ref} is set as 600 kVar. Finally set as 850 kVar at 0.5 sec. As per the reference the UPLM effectively controls the reactive power as shown in the simulation results.

Power frequency variation control: Here, the supply frequency is 60 Hz at normal condition. The permissible limit of the supply frequency is 59-61 Hz. In this supply frequency, the variation of the frequency sensitive components will be affected. When the supply frequency increases rapidly, the motor speed also increases. The

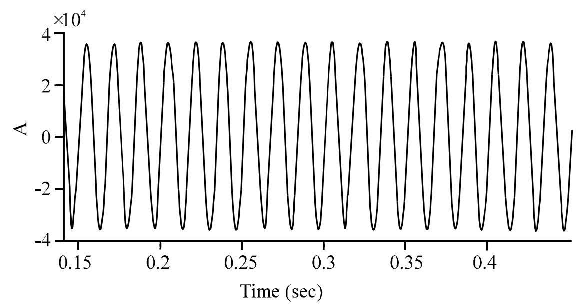

Fig. 7: Supply current after UPLM compensation

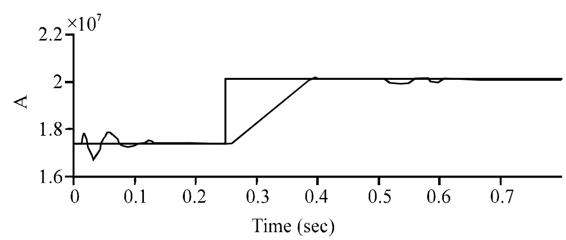

Fig. 8: UPLM controlled real power of the test system

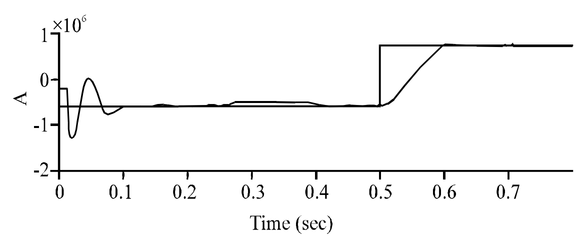

Fig. 9: UPLM controlled reactive power of the test system

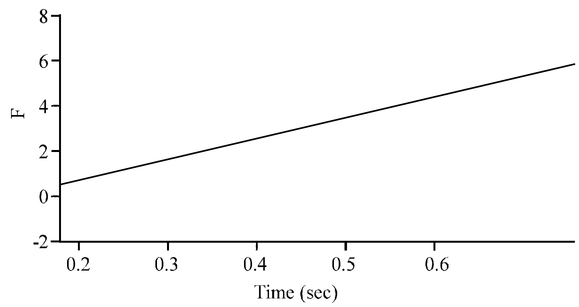

Fig. 10: Frequency error in supply frequency

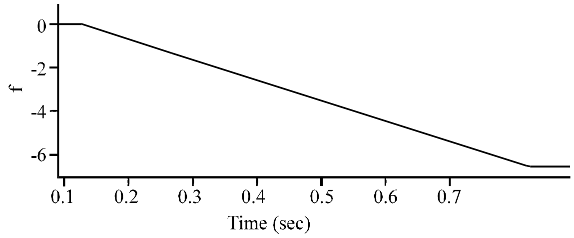

Fig. 11: PI controller output of matrix converter

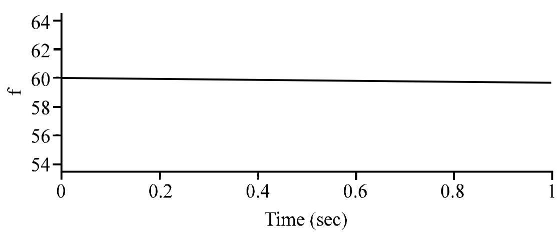

Fig. 12: Regulated frequency in load voltage

rated speed of induction motor is 1800 rpm. When the supply frequency increases, the speed of the induction motor also increases from 1800-1950 rpm. Figure 10 shows the error value of the supply frequency produced by the UPLM control system. This can be obtained from the UPLM control system. It is the difference between the supply frequency and the reference frequency. In Fig. 10, the reference value is 60 Hz. The frequency varying rapidly so, the error value also increases rapidly. The UPLM control system produced by the corresponding compensating value as shown in Fig. 11. The frequency is regulated by using PI controller in UPLM. Figure 12 shows the load voltage frequency. The supply frequency varies above or below the output frequency, i.e., load frequency is almost constant. In Fig. 12, the frequency is almost 60 Hz.

CONCLUSION

A new Universal Power Line Manager (UPLM) consists of universal power line conditioner and matrix converter based frequency compensator has been proposed in this study. This new power line manager having active filtering, real power flow control and reactive power flow, voltage regulation and frequency regulation are developed using the three converters. The proposed UPLM is a single equipment in which almost all compensation characteristics are included. In this study, the traditional instantaneous algorithm is used for more reliability and stability of the control system.

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