A CONTROL STRATEGY FOR UNIFIED POWER QUALITY CONDITIONER (UPQC) USING INSTANTANEOUS SYMMETRICAL COMPONENTS THEORY

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***Abstract* – A new control strategy for generation of reference compensating currents and voltages waveforms of unified power quality conditioner (UPQC) is presented. The control strategy is based on combination of instantaneous symmetrical component and pq theories. The operation of control circuit is explained using analytical computations. The steady state and dynamic operation of control circuit in different load current and/or utility voltages conditions is studied through simulation results. The presented method has acceptable dynamic response with a very simple configuration of control circuit.**

I. INTRODUCTION

The significant improvement of semiconductor technology since 1970, made it possible using these devices in electric utility applications. One of the recent developed of these applications is unified power quality conditioner (UPQC) [1]. According to the basic idea of UPQC, it consists of back-to-back connection of two three-phase active filters (AFs) with a common dc link. One of the AFs is connected in parallel with the utility and is called parallel active filter (PAF). The PAF works as current source and usually compensates for current quality problems of load and regulating of dc link. On the other hand, the second AF is connected in series with the utility and acts as series active filter (SAF) to compensate for voltage quality problems of utility. In this way, operation of UPQC isolates the utility from current quality problems of load and in the same time, isolates the load from voltage quality problems of utility.

Obviously, the most important subject in the operation of UPQC is the generation method of reference compensating currents of PAF and reference compensating voltage of SAF. Different control strategies are presented for UPQC [2-4] but to the best knowledge of authors, using the instantaneous symmetrical components is a new concept in this field. This paper deals with combination of instantaneous symmetrical components theory [5] and pq theory [6] for controlling of UPQC. The overall control method is very simple to implement. It does not need phase lock loop or complicate computations. The analytical analysis and simulation results are presented to study the operation of control circuit in dynamic and steady state cases.

II. CONTROL STRATEGY

Fig. (1) shows the general power circuit configuration of UPQC. This system consists of a PAF and a SAF. The control circuit of UPQC, generates the reference compensating currents and voltages of PAF and SAF in instantaneous and simultaneous manner, respectively.

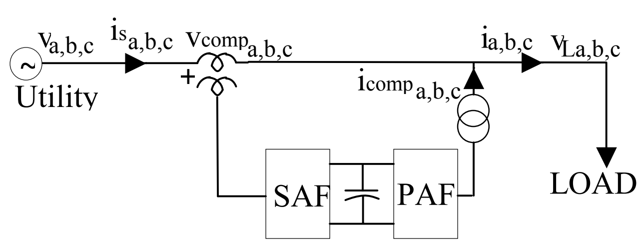

Fig. 1. General power circuit configuration of UPQC

Fig. 2 shows the proposed control circuit of UPQC. In this figure the notations of i_a, i_b, i_c and v_a, v_b, v_c stand for instantaneous load side currents and utility side voltages, respectively. The operation of control circuit results in generation of instantaneous reference compensation currents of PAF i^*_{compa}, i^*_{compb} and i^*_{compc} and instantaneous reference compensating voltages of SAF

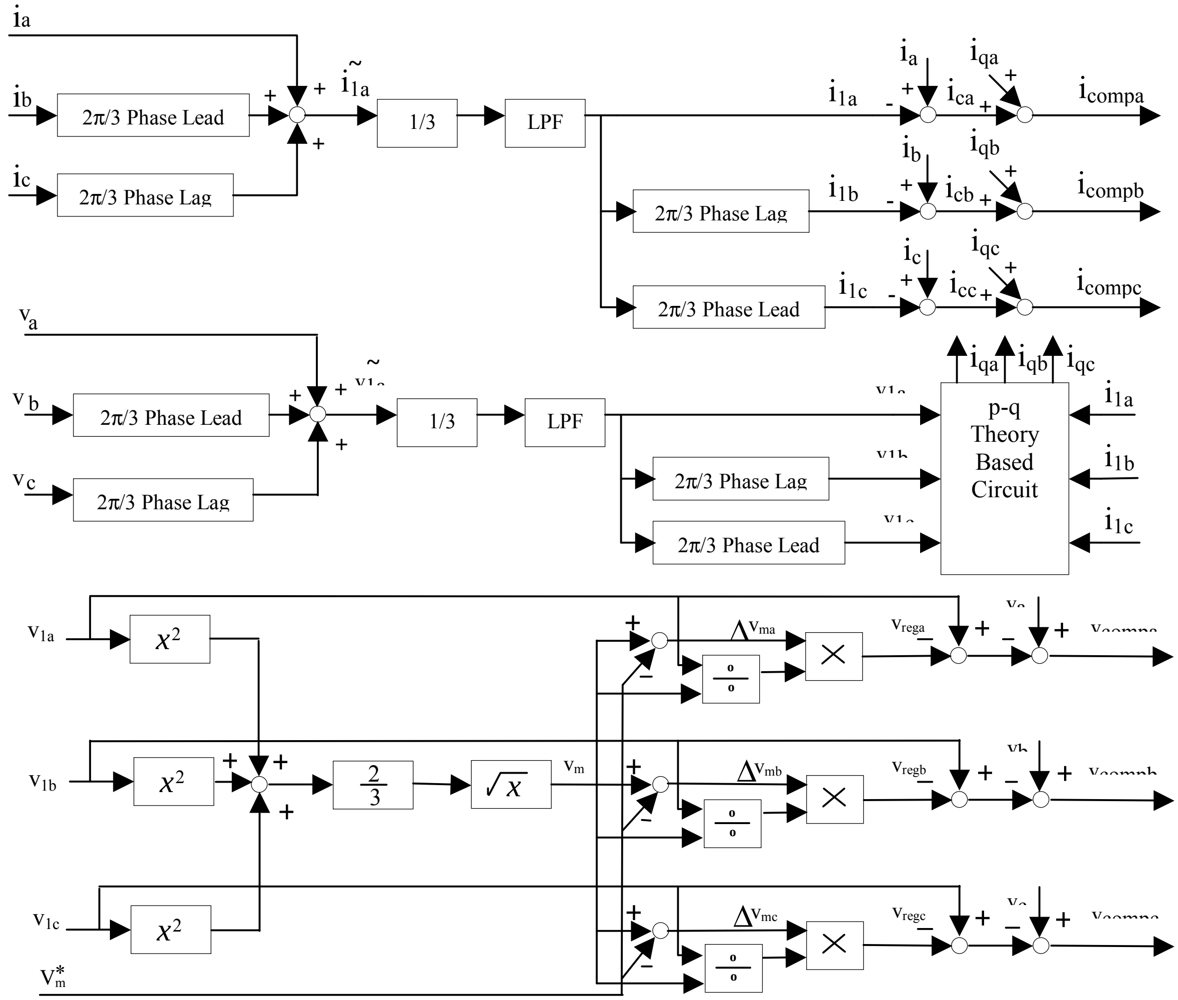

Fig. 2. Control circuit of UPQC based on combination of instantaneous symmetrical component and pq theories

v^*_{compa}, v^*_{compb} and v^*_{compc} in the phases a, b and c, respectively.

The following sections of this part explain the operation of control circuit of PAF and SAF, separately.

II-I- CONTROL CIRCUIT OF PAF

The symmetrical component theory originally defined for steady-state analysis of 3-phase unbalanced systems. This transformation is the result of multiplying the transformation matrix of eq. (1) by the phasor presentation of unbalanced 3-phase system of eq. (2).

$$A=\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix} \qquad (1)$$

Where; $a = e^{j2\pi/3}$.

$$\begin{bmatrix}V_0\\ V_1\\ V_2\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix} \qquad (2)$$

The V_0, V_1 and V_2 stand for phasor presentation of zero, positive and negative sequence components of phase-neutral voltage in the phase "a", respectively. The V_a, V_b and V_c stands for phasor presentation of voltages of phases a, b and c, respectively. It is possible using this transformation in instantaneous manner, easily [5, 7]. There are similar expressions for currents, too.

The first part of control strategy of PAF is based on computing of instantaneous positive sequence of load side currents and utility side voltages using instantaneous symmetrical component theory. A low pass filter (LPF) that its cutoff frequency is equal with fundamental frequency (i.e. 60 Hz) is used to rejection of harmonics. In this way, it is possible to get the instantaneous positive sequence of fundamental current/voltage of phase "a" i_{1a+} and v_{1a+}, easily. According to this fact that the harmonics of current/voltage are rejected by LPF, it is not important considering their condition in previous control blocks.

Instantaneous positive sequence of currents/voltages in the phases "b" and "c" obtains using $2\pi/3$ phase lag and $2\pi/3$ phase lead blocks, respectively. In Fig. (2), the notations of i_{1b+}, i_{1c+}, v_{1b+} and v_{1c+} stand for the instantaneous positive sequence of fundamental currents and voltages in the phases "b" and "c".

The reference compensation currents of PAF (without considering the reactive power compensation of load), i_{ca}, i_{cb} and i_{cc} in the phases a, b and c, respectively obtains using the following equations:

$$i_{ca} = i_a - i_{1a+} \quad (3)$$
$$i_{cb} = i_b - i_{1b+} \quad (4)$$
$$i_{cc} = i_c - i_{1c+} \quad (5)$$

For instantaneous reactive power compensation purpose, it is possible using pq theory [6]. Fig. 3 shows the p-q theory based circuit. In this way, the reference reactive power compensation currents, i_{qa}, i_{qb} and i_{qc} obtains in each of the phases a, b and c, respectively.

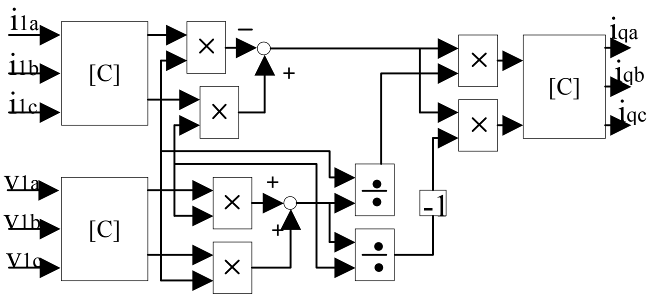

Fig. 3. pq theory based instantaneous reactive power compensation circuit

The overall reference compensation currents of PAF results from the following expressions in each of the phases a, b and c, respectively.

$$i^*_{compa} = i_{ca} - i_{qa} \quad (6)$$
$$i^*_{compb} = i_{cb} - i_{qb} \quad (7)$$
$$i^*_{compc} = i_{cc} - i_{qc} \quad (8)$$

II-II- CONTROL CIRCUIT OF SAF

Subtraction of v_{1a+}, v_{1b+} and v_{1c+} from v_a, v_b and v_c, respectively, can be used for computation of reference compensation voltages of SAF. But, in this case, it is not possible regulating the magnitude of voltage at the load side. Eq. (9) gives the magnitudes of v_{1a+}, v_{1b+} and v_{1c+}, $v_m(t)$, which are equal with each other, instantaneously:

$$v_m(t) = \sqrt{\frac{2}{3}(v_{1a+}(t)^2 + v_{1b+}(t)^2 + v_{1c+}(t)^2)} \quad (9)$$

Subtraction of V^*_m, which is the reference value for the magnitude of voltages at the load side, from $v_m(t)$ results in the magnitude error that is shown by the term of $\Delta v_m(t)$ in Fig. 2. Dividing v_{1a+} by $v_m(t)$ and multiplying it with $\Delta v_m(t)$ results in $v_{rega}(t)$ that is the necessary regulating voltage of SAF in the phase of "a". This regulating voltage is in phase with v_{1a+}. Finally the following formula can be used for determination of reference compensating voltages of SAF in the phase of "a" that is shown by $v_{compa}(t)$ in Fig.2. There are similar procedures for phases "b" and "c", too [7].

$$v_{compa}(t) = v_a(t) - v_{1a+}(t) + v_{rega}(t) \quad (10)$$

III- EXPLANATION OF OPERATION OF 2π/3 PHASE LEAD/LAG CONTROL BLOCKS

Fig. 4 shows the operation of "$2\pi/3$ phase lead" control blocks of Fig. 2 in detail. The terms of $v_i(t)$ and $v_{o+}(t)$ are as input and output functions of this block. The magnitudes of K and T are $-\sqrt{3}/2$ and $1/\omega_1$, respectively. The term of ω_1 shows the fundamental angular frequency.

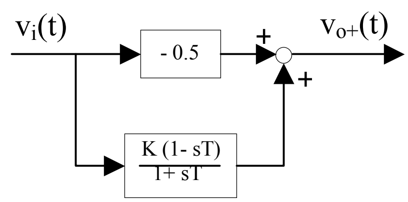

Fig. 4. Explanation of $2\pi/3$ phase lead control block

The relation between $v_i(t)$ and $v_{o+}(t)$ in the time domain can be explained using eq. (11) [7].

$$v_{o+}(t) = \left(\frac{\sqrt{3}-1}{2}\right) v_i(t) - \sqrt{3}\,\omega_1 e^{-\omega_1 t} \int_0^t v_i(\tau).\, e^{\omega_1 \tau}\, d\tau \quad (11)$$

Eq. (12) explains the relation between input and output functions of "$2\pi/3$ phase lag" blocks of Fig. 2. This equation is obtained in a similar manner as eq. (11) by changing the value of K to $\sqrt{3}/2$.

$$v_{o-}(t) = -\frac{\sqrt{3}+1}{2} v_i(t) + \sqrt{3}\,\omega_1 e^{-\omega_1 t} \int_0^t v_i(\tau).\, e^{\omega_1 \tau}\, d\tau \quad (12)$$

The term of $v_{o-}(t)$ stands for the output of $2\pi/3$ phase lag control block.

Using eq.s (11) and (12) and considering the operation of low pass filter it is possible writing eq. (13) as follows:

$$v_{1a+}(t) = \frac{1}{3}\left[v_{1a}(t) + \frac{\sqrt{3}-1}{2} v_{1b}(t) - \frac{\sqrt{3}+1}{2} v_{1c}(t) + \sqrt{3}\omega_1 e^{-\omega_1 t} \int_0^t (v_{1c}(\tau) - v_{1b}(\tau))\, e^{\omega_1 \tau}\, d\tau \right] \quad (13)$$

The notation of $v_{1a+}(t)$ shows the instantaneous positive sequence of fundamental frequency of phase "a". The terms of $v_{1a}(t)$, $v_{1b}(t)$ and $v_{1c}(t)$ stand for fundamental frequency of voltage in the phases a, b and c, respectively. The last term of eq. (13) shows a damping transient case with the time constant of $1/\omega_1$. This is the reason, which this method can be considered as a *quasi*-instantaneous method [7]. It is possible writing eq.s (11) to (13) for currents in a similar manner.

IV. EXPLANATION OF OPERATION OF LOW PASS FILTER (LPF)

The low pass filter (LPF) block that is shown in Fig. 2 consists of series connection of four LPFs by itself. This circuit is shown in Fig. 5 in detail.

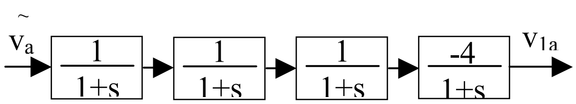

Fig. 5. The Control blocks of LPF

The cutoff frequency of all of individual filters is set on fundamental frequency. This results in $-\pi/4$ phase shift and $1/\sqrt{2}$ amplitude changes of fundamental frequency at the output of each of individual LPF. In this way, the operation of overall circuit results in $-\pi$ phase shift and $1/4$ magnitude change of fundamental frequency. Considering the gain of final LPF equal with –4, compensates for these problems and makes it possible to extract the fundamental frequency without any phase shift or magnitude change [7].

V. SIMULATION RESULTS

Operation of control circuit of Fig. 2 is simulated using the power circuit of Fig. 6. The load side currents and utility side voltages of this circuit fed as input quantities to the control circuit of Fig. 2.

The utility of Fig. 6 consists of a three-wire three-phase 120 (V) (RMS, L-N), 60 Hz utility, a three-phase balanced R-L load, a three-phase diode rectifier with R-L load that is possible to switch it ON/OFF using a three-phase static switch and a single-phase resistive load that is possible to switch it ON/OFF using a single phase static switch. This circuit has five stages of operation as follows:

1- The load of utility from zero until 0.05 (s) is only the three phase-balanced R-L load.
2- The three-phase diode rectifier is switched ON at 0.05 (s) by operation of static switches and produces harmonics and increases reactive power demand too.
3- At 0.1 (s), the single-phase resistive load is switched ON and generates an imbalance current case. This load is switched OFF at 0.15 (s).
4- In the same instant (i. e. 0.15 (s)), until the last of simulation at 0.2 (s), the RMS of voltage in the phase "a" is reduced to 70 (V) to generate an imbalance utility voltage case.
5- From 0.2 (s) to 0.25 (s) three phase fifth order voltage harmonics with the magnitude of 16.6% of fundamental frequency of (i.e. 20 V) is added to the supply.

A number of selected simulation results are shown in Fig. 7. Fig. 7(a) to 7(d) show the utility side voltages, reference voltages at load side, load side currents and reference currents at source side, respectively.

The reference voltages magnitude V^*_m, at the load side is set on 170 (V). Comparison Fig. 7(a) with Fig. 7(b) show that in all of the stages of circuit operation the reference load side voltages are sinusoidal, balanced and regulated on 170 (V). The control method has an excellent dynamic response, too.

Comparison Fig. 7(c) and 7(d) shows that in all of the circuit operation stages, the reference source side currents are sinusoidal, balanced. This conditions covers utility voltage quality and load current quality conditions. These currents are in phase with the instantaneous positive sequence of utility side voltages, which means reactive power compensation, instantaneously. This subject is visible considering Fig. 7(a) and 7(d) from zero to 0.15 (sec) which the utility voltages and their instantaneous positive sequences are similar. The system has a reasonable dynamic response in compensation for current quality problems too.

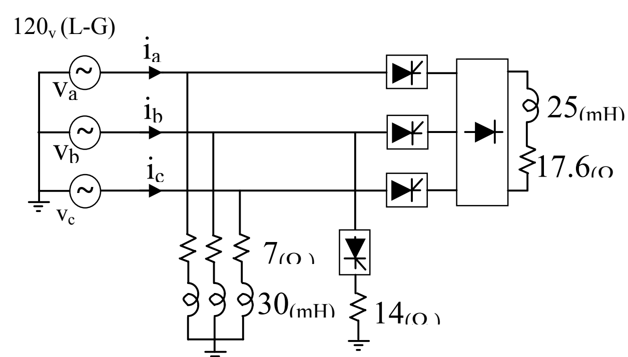

Fig. 6. Simulated power circuit

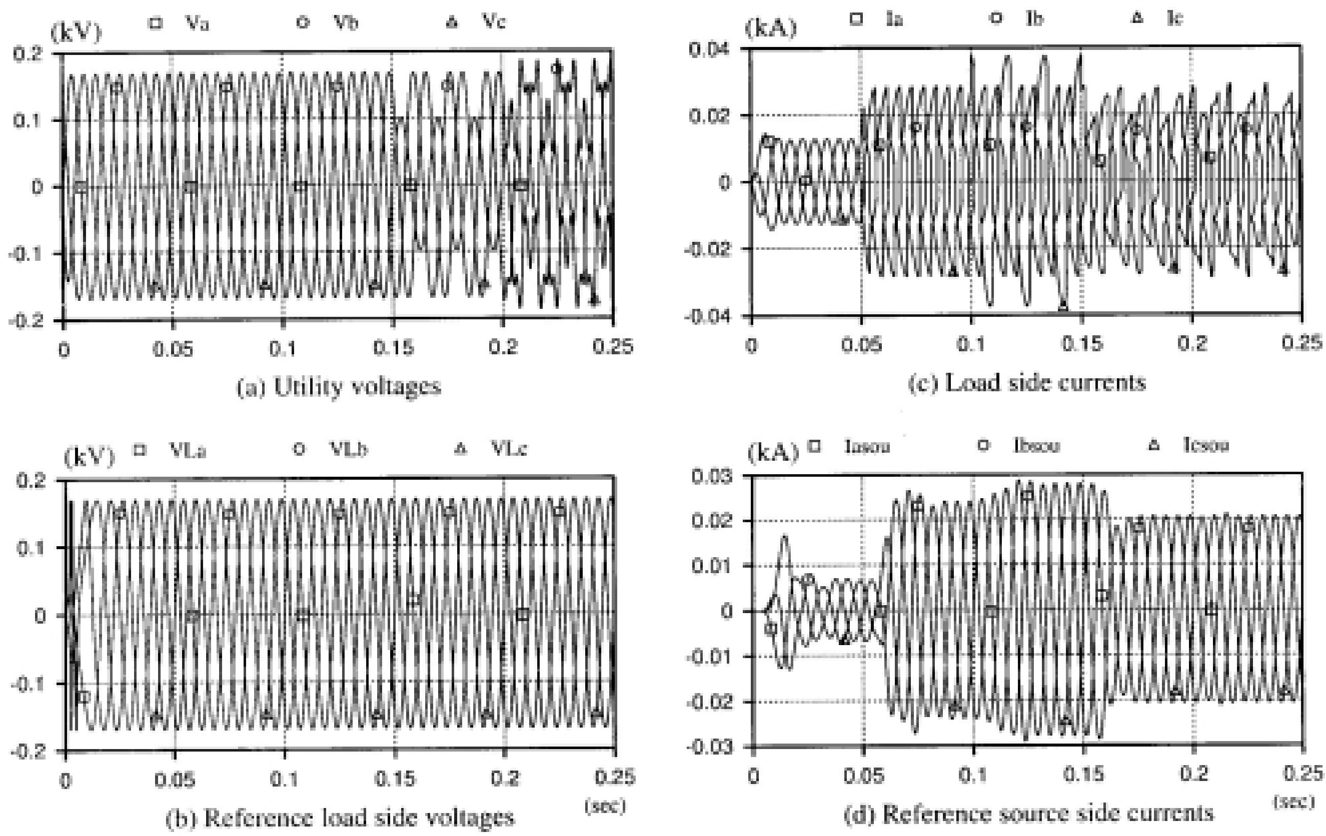

Fig. 7. Simulation results

VI. CONCLUSION

A new control strategy for UPQC is presented. This method is easy to implement and it has reasonable dynamic response. The control strategy generates reference compensating currents of PAF and reference compensating voltages of SAF in such a manner that the source side currents and load side voltages become sinusoidal and balanced in various power quality conditions. The system compensates for instantaneous reactive power using pq theory, too. The analytical expressions and simulation results explain the circuit operation and the validity of presented method.

VII. REFERENCES

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