A New Proposal For Simplified Control Technique Of Dual Open UPQC

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ABSTRACT : Power quality (PQ) is very important to certain customers. For this reason, many utilities could sell electrical energy at different prices to their customers, depending on the quality of the delivered electric power. Since most end users are connected to secondary. Currently, the quality of supplied power is important to several customers. Power quality (PQ) is a service and many customers are ready to pay for it. Different from a conventional UPQC, the open UPQC has the series filter controlled as a sinusoidal current source and the shunt filter controlled as a sinusoidal voltage source. Therefore, the pulse width modulation (PWM) controls of the open UPQC deal with a well-known frequency spectrum, since it is controlled using voltage and current sinusoidal references, different from the conventional UPQC that is controlled using non sinusoidal references. In the future, distribution system operators could decide, or could be obliged by authorities, to supply their customers with different PQ levels and at different prices. A new device that can fulfill this role is the OPEN unified power quality conditioner (UPQC), composed of a power-electronic series main unit installed in the medium-voltage/low-voltage (LV) substation, along with several power-electronic shunt units connected close to the end users.

INTRODUCTION

Power quality (PQ) is very important to certain customers. For this reason, many utilities could sell electrical energy at different prices to their customers, depending on the quality of the delivered electric power. Since most end users are connected to secondary distribution networks, at low voltage (LV), it could be important to monitor and compensate the main disturbances on the LV grid. Specifically, it has been reported in a survey that, in the Southeastern region of the U.S., most monitored industrial customers and main end users did not suffer long outages. Rather, they experienced numerous short duration voltage sags and momentary interruptions. Therefore, local utility companies had to re-configure their systems to keep their most important customers on-line.

However, these devices do not allow local distributors to guarantee different quality demand levels to the final customers, because they improve power quality for all the supplied end users. The installation investments are also quite high relative to the power quality level obtained. A solution that has similar performances and advantages, but also makes cost reduction possible, is the proposed OPEN UPQC. This new solution, analyzed in, starts from the UPQC configuration, removes the common dc connection and splits the shunt unit into several shunted devices.

DESIGNING STRUCTURE OF THE OPEN UPQC: Most end user disturbances are characterized by short duration and small amplitude, though they can still cause interruptions in production processes. Most voltage sags have small depth and short durations. More than 95% of voltage sags can be compensated by injecting a voltage of up to 60% of the nominal voltage, with a maximum duration of 30 cycles. This information is primarily used to evaluate a suitable size for the OPEN UPQC.

The series unit of the OPEN UPQC, sized to supply 60% of the LV network power and equipped with a small storage system, can compensate for most of the voltage disturbances.

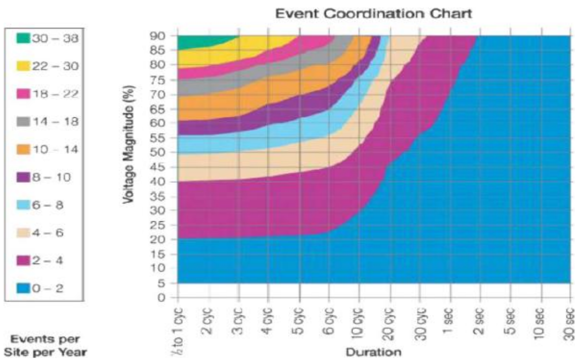


Fig.1. Example of distribution of voltage disturbances reported in the EPRI event coordination chart

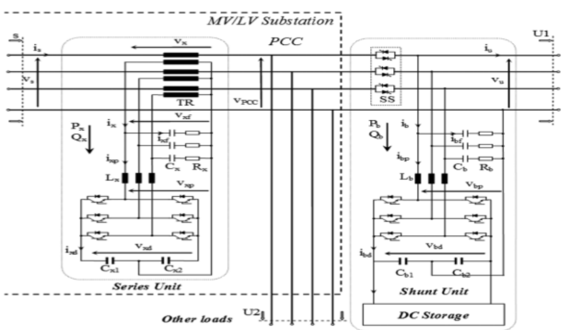


Fig. 2. Multiwire power diagram of the new proposed solution.

Each shunt unit is sized in relation to the supplied load power, and can protect its sensitive load against interruptions. The shunt unit's function is similar to that of the UPS output stage, but is less expensive because it only has one conversion stage and involves less power loss. The series unit consists of a coupling transformer (TR), with the primary circuit connected in series with the mains line and a secondary one supplying the reversible ac/dc power converter. The output stage of the pulse width modulation (PWM) voltage controlled converter contains passive RC shunt filters, to compensate for the harmonic currents at switching and multiple frequencies. Neglecting the *a*ctive power to compensate the converter losses, the series unit is controlled to act as a purely reactive inductor when the supply voltage is within its operation limits. This fact is of fundamental importance, because in this range the loads must be supplied by the mains 95% of the time, as established by the IEEE Std 1159 "IEEE Recommended Practice for Monitoring Electric Power Quality" and European EN50160; therefore, the storage system must not discharge itself. Outside of this range, *active* power can be used to compensate the disturbances, in the same way as the usual series compensation devices, when a storage system is present.

The shunt units consist of an ac/dc power converter, similar to the one used in the series unit, connected to an energy storage system and a set of static switches (SS). The shunt unit, depending on the state of the network voltage, can supply either the entire load, or a part of the load. There are two different modes of OPEN UPQC operation:

- **COMPENSATOR:** when the PCC voltage is within its operation limits, the SS are closed, the series unit works as a three phase voltage generator and the shunt units work as current generators.

- **BACK-UP**: when the PCC voltage is outside of its operation limits, the SS are open, decoupling the network and the load-compensator system. Each sensitive load is supplied by its shunt unit, which acts as a sinusoidal voltage generator, using the energy stored in the storage system as an energy source.

OPEN UPQC PERFORMANCE

This section is focused on understanding the OPEN UPQC compensation limits. The analysis will be carried out under steady state conditions, to evaluate the compensation capacity of the device in normal operation mode $0.9\cdot V_n \le V_s \le 1.1\cdot V_n)$. It is important to remember that the power absorbed by the loads and the shunt units influences the performance of the series unit, and therefore of the whole OPENS UPQC.

Therefore, when considering a particular set of load conditions, it is possible to find operating conditions for the shunt units that increase the compensating limits of the series unit. Depending on whether or not storage systems are present, the series and shunt units can exchange only non active power or both non active power and active power with the mains. In the latter case, as will be shown in the following, the OPEN UPQC can better compensate for short duration disturbances.

In the following cases, all of the solutions will be analyzed under the assumption that the voltages are sinusoidal and are constituted of only the positive sequence component in the different network buses. It is important to emphasize that suitably coordinating the various units of the OPEN UPQC allows for a wide compensation range, comparable with the UPS, but more economical.

This coordination requires a communication system (i.e., based on the carrier waves) between the series unit and the shunt units, but this system cannot be very fast. Moreover, in transient analysis, the communication between the series unit and the shunt units cannot be included (the communication could be slow, could be out of order, etc.). Therefore, each unit necessarily works alone.

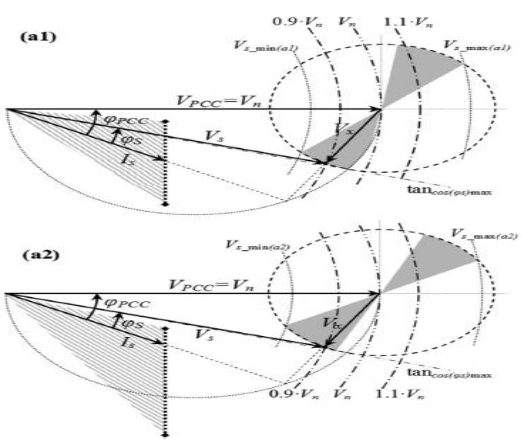


Fig.3 Voltage compensation, exchanging only nonnative power. Case (a1): it is possible to obtain a power factor equal to 1 in s section in low-voltage situations. Case (a2): the power factor is always less than 1.

NONNATIVE AND POWER EXCHANGE

The conditions under which all of the converters exchange only non active power must be confirmed in situations when the system voltage Vs is near the contractual limits (normal operation mode). In normal operation mode, the maximum voltage drop in the LV lines of the network must be less than 5% to maintain low power loss. Therefore, if all the converter units are operating to stabilize the voltage in the PCC at its nominal value (100%), the load voltage value will be at least 95% of the nominal voltage.

This result allows an improvement of one of the aspects of the supply quality, the stability of the real value of the supply voltage, for all customers. Therefore, the OPEN UPQC works to stabilize the nominal voltage at the PCC. The phasor diagram of the OPEN UPQC is shown in Fig. In order to avoid active power injections, the series voltage has to be in quadrature with the mains current.

$$\overline{V}_x = \overline{V}_{\mathrm{PCC}} \cdot \frac{\sin(|\varphi_{\mathrm{PCC}} - \varphi_S)}{\cos(\varphi_S)}. \quad (1)$$

The current Is is primarily composed of the current of unprotected loads Us (whose phase difference with respect to Vpcc cannot be varied) and the current of protected loads (whose phase difference with respect to Vpcc can be changed by the shunt units) as reported in (2), where Pu12 and Qu12 are the active and reactive power of the equivalent load respectively, Plosses m and Qlosses are the active and reactive power lines losses, respectively, and Qb is the reactive power injected by all the shunt units

$$\underline{I}_s = \frac{P_{U1}+P_{U2}+P_{losses}+j\cdot(Q_{U1}+Q_b+Q_{U2}+Q_{losses})}{\overline{V}_{\mathrm{PCC}}}. \quad (2)$$

Therefore, the angle φ_{PCC} can oscillate between the upper and lower limits $\varphi_{\mathrm{PCC\_max}}$ and $\varphi_{\mathrm{PCC\_min}}$, $Q_b = A_1$ and $Q_b = -A_1$ obtained when and respectively, in the area highlighted in Fig. 4. The angle can be calculated by the equation shown at the bottom of the page.The current phasor Ia can move along the black dotted line, varying the reactive power $Q_b$of the shunt units. In case (a1) in particular, it is possible to obtain a power factor equal to 1 in the section in low voltage situations, because the line $\tan_{\cos(\varphi s)\max}$ intercepts the black dotted line. In case (a2), the power factor is always less than 1. The quantities $V_{s\_\max}$ and $V_{s\_\min}$ can be obtained with (4) and (5), as shown at the bottom of the page.

Assuming that , the range $V_{s\_\max} + V_{s\_\min} \approx 2 \cdot V_{\mathrm{PCC}}$, $V_{s\_\max} - V_{s\_\min}$ the range amplitude can be obtained with

$$V_{s\_\max} - V_{s\_\min} \approx 2 \cdot V_{x\_\max} \cdot \sin(\varphi_{\mathrm{PCC}\_\max}). \quad (6)$$

It can be seen that the compensating range amplitude $V_{s\_\max} - V_{s\_\min}$ depends on the $V_{x\_\max}$ value that the series unit can inject, and on the non active power. The non active power is susceptible to exchanges by the shunt units (length of the black dotted line, proportional to the loads U_1 apparent power) and to the power factors of the equivalent loads U_1 and U_2. .

In normal operation mode, the compensation strategy can be implemented in various ways. For example, power factor maximization in the s section (corresponding to minimization of the current Is) is a compensation strategy that can be implemented by coordinating the series unit and the shunt ones. Therefore, communication between all the units is required.

The simplest solution is to employ a slow communication system that allows the OPEN UPQC to stabilize the voltage at the PCC, maximizing the power factor in normal operation conditions and increasing its compensation limits outside of normal operation. Obviously, in the case of large disturbances in that the series unit cannot compensate, each shunt unit can supply the load in back-up mode.

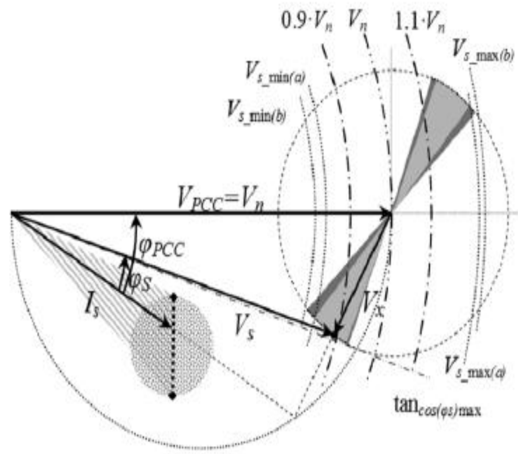


Fig. 5. Compensation limits of the OPEN UPQC: with *nonactive* power exchange only (light gray) and with also *active* power exchange (dark gray) by the shunt units.

NONNATIVE Qb AND Qx AND ACTIVE Px POWER EXCHANGE

In this case, the series converter produces only non active power, but the shunt units can exchange active and non active power with the mains. This condition could be represented as an active network into which dispersed generations are inserted. Fig. 5 depicts the new phasor diagram of the OPEN UPQC under the above operating conditions.

In order to avoid active power injections by the series unit, the voltage Vx and the mains current Is have to be in quadrature with each other. In Fig. 5, the light grey areas indicate the field in which Vx can lay without active power exchanges by the shunt units, and the dark gray areas indicate the possible values of with active power exchanges by shunt units. In this case, the compensating range amplitude $V_{s\_\max} - V_{s\_\min}$ is greater than without active power exchanges, but it is important to note that the difference is small. The phasor current can move inside of the gray dotted circle, varying the active and non active power of the shunt units (movement on the black dotted line regards only non active power exchange).

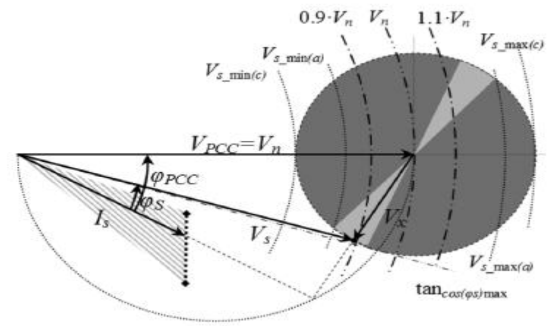


Fig. 6. Compensation limits of the OPEN UPQC: with *nonactive* power exchange only (light gray) and with also *active* power exchange (dark gray) by the series unit.

NONCCTIVE Qb AND Qx AND ACTIVE Px POWER EXCHANGE

In order to exchange active power with the mains, a storage system connected to the dc section of the series unit is needed. The storage system size does not need to be very large, because little energy is required to compensate most of the disturbances For example, to compensate most of the voltage variations reported in Fig. 2 (voltage sag 60% deep for 30 cycle) for a 400-kW load, an energy equal to 120 kJ is needed, corresponding to a battery capacity of about 0.4 Ah at 96 V or a capacitor or super capacitor bank of about 1.5 F at 400 V. Given a storage system with twice the abovementioned capacity, in order to allow bidirectional energy exchange with the mains, it is possible to compensate voltage disturbances in that are outside of the contractual limits. In the case of mains interruptions lasting longer than 30 cycles, the SS of the shunt units switch off, and the loads are supplied in back-up mode Considering compensation of transient disturbances, such as voltage sags, swells, etc., various compensation strategies are available for the OPEN UPQC, including minimizing the energy required by the storage system of the series unit. The new phasor diagram of the OPEN UPQC operation is shown in Fig. 6. In the light gray areas, the series voltage and the mains current have to be in quadrature with each other, because active power exchanges by the series unit are not allowed.

In these areas, the behavior of the OPEN UPQC is the same as that of the cases described previously. In the case of transient disturbances, the series unit can compensate the voltage over a very large range (the compensating range amplitude is $V_{s-\max(c)} - V_{s-\min(c)}$)) compared with all the cases previously analyzed. Indeed, the series unit can exchange active power with the mains in the dark gray areas, but this is only possible for transient disturbances due to the small size of the series unit storage system.

CONTROL STRATEGY

The following describes a control strategy that can be employed in normal operation mode $(0.9 \cdot V_n \leq V_s \leq 1.1 \cdot V_n)$, , under steady state conditions, and elucidates the device performance. The dynamic response during transient events has not been considered in this work, because it is described in detail in. For example, considering the dynamic behavior of the series unit, it can be seen that the series unit cannot be affected by the shunt units during a transient event. This is due to the fact that the communication system between them is slow, and does not allow a fast coordinated control strategy.

In order to compensate for the voltages in normal operation, the strategy that maximizes the power factor $\cos(\varphi_s$ (corresponding to the current minimization) can be chosen. With this choice, it is possible to minimize the apparent power required by the mains. The mains current Is is reported in (2), and the compensated voltage Vpcc is

$$\overline{V}_{\mathrm{PCC}} = \overline{V}_s - \overline{V}_x. \qquad (7)$$

Neglecting power losses and considering that the voltage has to be in quadrature with the current , it is possible to write the following relation:

$$\underline{I}_s = \frac{P_{U1} + P_{U2} + j \cdot (Q_{U1} + Q_b + Q_{U2})}{\overline{V}_s - j \cdot x \cdot \overline{I}_s} \qquad (8)$$

Where is the equivalent reactance of the series unit, giving a voltage proportional to . Solving (7) and (8) is not mathematically easy due to the nonlinearity of the problem, and implementing them into a controller is not useful. It is more convenient to implement two PI controllers: one to evaluate the voltage of the series unit, and another to evaluate a signal related to the non active power that all of the shunt units have to inject.

The conditions under which the series unit can exchange only nonactive power can be obtained by applying the Park transform to the three phase currents I_{s-a}, I_{s-b} and I_{s-c}, , and , and calculating the two components and in a rotating reference frame, as reported in (9)

$$\begin{bmatrix} I_{s-d} \\ I_{s-q} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta + \frac{2}{3}\pi\right) \end{bmatrix} \cdot \begin{bmatrix} I_{s-a} \\ I_{s-b} \\ I_{s-c} \end{bmatrix} \quad (9)$$

$$V_{x-d} = -K_{Vx} \cdot I_{s-q}$$
$$V_{x-q} = K_{Vx} \cdot I_{s-d}. \quad (10)$$

For the constant Kvx to be independent of the load conditions, the previous expressions must be normalized with respect to the load current module

$$V_{x-d} = -K_{Vx} \cdot \frac{I_{s-q}}{\sqrt{I_{s-d}^2 + I_{s-q}^2}}$$
$$V_{x-q} = K_{Vx} \cdot \frac{I_{s-d}}{\sqrt{I_{s-d}^2 + I_{s-q}^2}}. \quad (11)$$

The constant K_{Vx} is obtained by a PI controller that keeps the voltage at the output of the series unit V_{PCC} equal to the rated value V_{ref}, as reported in the block diagram of Fig. 7. The second control loop acts to minimize the angle φ_s between the voltage and the current downstream of the MV/LV transformer, in order to maximize the power factor absorption in the section. In this case, the PI controller produces a signal K_{Qb},

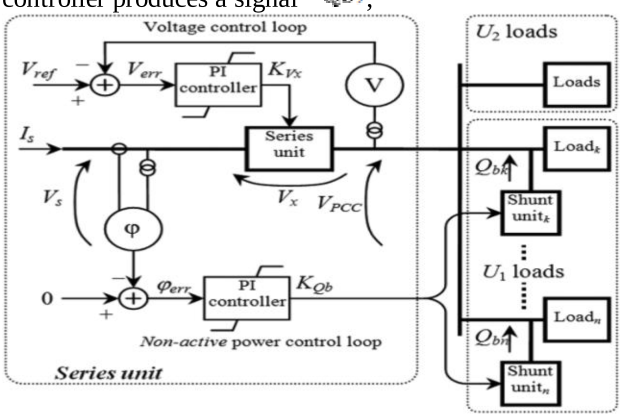


Fig.6 Voltage control loop of the series unit and nonactive power control loop of the shunt units in the OPEN UPQC system

which varies from 0 to 1, and is equal to the ratio between the desired non active power inject able by the shunt units and the maximum inject able non active power. This signal is sent to all shunt units by the communication system. Thus, the injected non active power of the th shunt unit Q_{bk} is equal to

$$Q_{bk} = K_{Qb} \cdot A_k \quad (12)$$

Where Ak is the unit's rated power. The total non active power injected by all the shunt units is

$$Q_b = \sum_{k=1}^{n} Q_{bk}. \quad (13)$$

Obviously, this compensation strategy, which is useful for its fast series unit response, requires non active power injection by the shunt units to be capable of achieving a wide compensation range. To enhance the entire system's performance, the power losses and the voltage drops in the LV lines generally must increase. However, if the power factor at the is PCC kept high (0.8), these increments are negligible. Moreover, this increment can be reduced by sending a different signal Kqbk to each shunt unit. This allows the closest shunt units to be used to inject more non active power, avoiding useless non active power flows.

SIMULATION DESIGN OF CASE STUDY

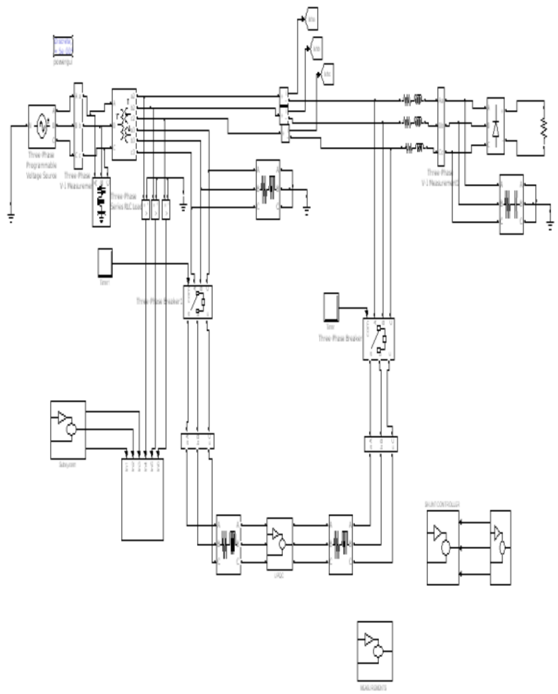


Fig.7 Simulink model of OUPQC

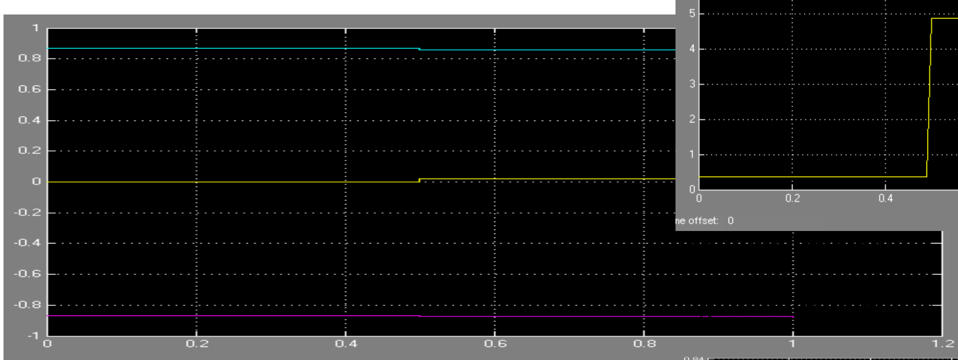
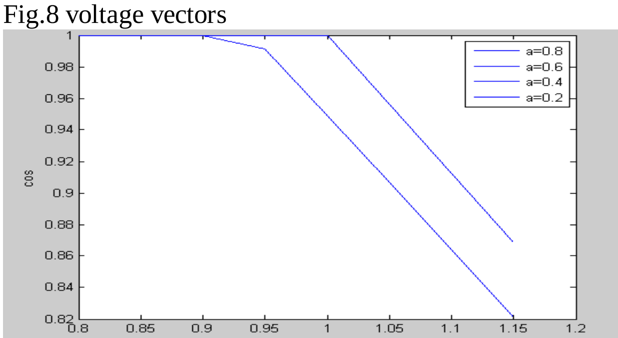


Fig.8 voltage vectors



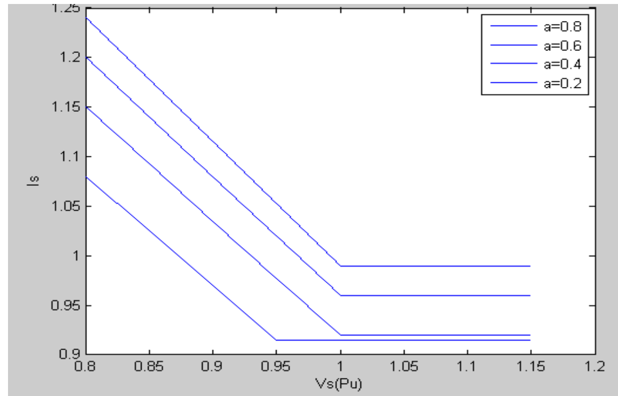
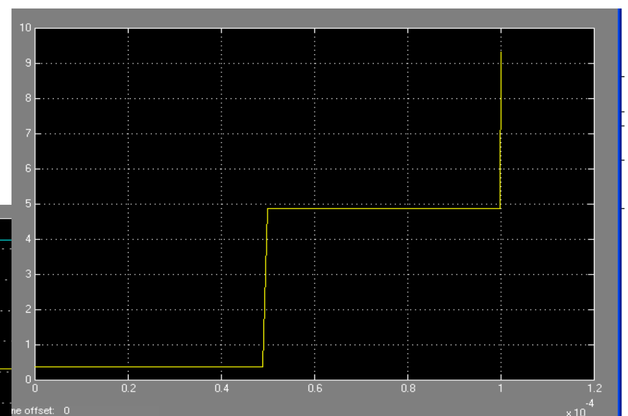


Fig.9 Power factors of the system and maximum line currents in case 1, for different α values.



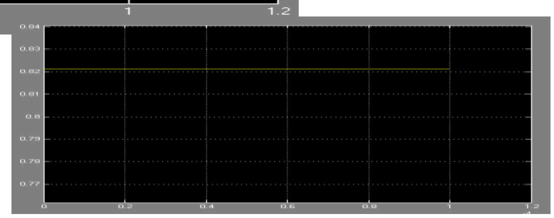


Fig.12 power factor

CONCLUSION

The OPEN UPQC apparatus is a good compensation system if wide installation of shunt units is needed. An increase in the percentage of the protected load enhances the voltage stabilization interval over which the OPEN UPQC can significantly improve the power quality, especially if the load power factor takes a high value. If the power factor of load is less than one, the power factor in section increases, to avoid nonnative power absorption from the mains. For low values of the parameter, the OPEN UPQC becomes expensive if there are few shunt units. In this case, it is better to install other compensation device typologies (as UPS, UPQC, etc.) near the sensitive loads, and a nonnative compensator system near the nonsensitive loads if necessary.

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