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A New Control Algorithm for UPQC for PQ Improvement

Satyanarayana Addala, Assistant Professor,Dept of EEE,Scet-Narsapur
Madan Mohan Chodavarapu, Assistant Professor,Dept of EEE,Scet-Narsapur
Dr.J.Mahil, Professor, Dept of EEE,Scet-Narsapur

***Abstract*— The optimal sizing of the unified power quality conditioner (UPQC) system has been investigated in this paper. The optimal VA ratings of the transformer and series/shunt converter of the UPQC system are designed by a two-level algorithm. The UPQC-P and UPQC-VA_{min} based systems are chosen as the benchmarks in this paper. Furthermore, the displacement angle control (DAC) is utilized to minimize the overall VA loading of the power converters for all operational points. Finally, the corresponding controllers are developed for the designed systems.**

Keywords*— *unified power quality conditioner (UPQC); displacement angle control (DAC);

I. INTRODUCTION

The most common voltage problem, i.e., voltage sag can cause irreversible damages to the critical loads, which leads to undesired financial loss [1], [2]. Moreover, the current and voltage harmonic distortions become severer due to the nonlinear power load. The power quality (PQ) of the system is degraded by the harmonics. The power factor also becomes worse. The power factor correction capacitor, motor, and transformer can be overheated due to the distorted current in the power system. The protective relay may be tripped more frequently. The accuracy of smart meter will also be reduced. Thus in the power system, maintaining the PQ of the source becomes an important task [1], [2].

The dynamic voltage restorer (DVR) can handle the voltage related PQ problems by injecting series voltages in the distribution line [3]-[5]. The distribution static compensator (DSTATCOM) is able to compensate the load harmonic current and reactive power by injecting shunt currents [6]-[8]. However, both the DVR and DSTATCOM can only deal with one of the voltage and current PQ problems.

The Unified Power Quality Conditioner (UPQC) is proposed to deal with both the voltage and current PQ problems [9]. The schematic diagram of UPQC is presented in Fig. 1. The UPQC consists of three modules, which are shunt converter, series converter, and transformer. The shunt converter deals with the current compensation. The series

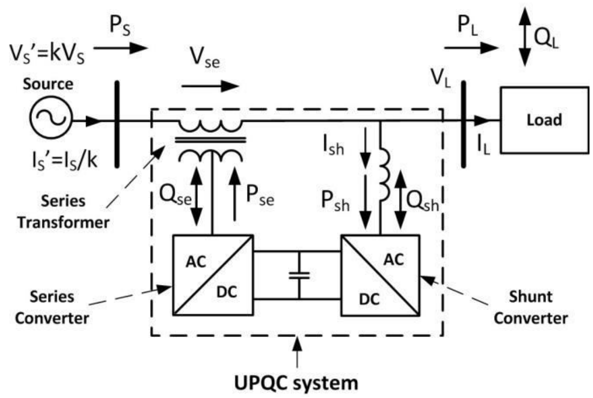

Fig. 1. UPQC general block diagram configuration.

converter can compensate the polluted source voltage. The transformer handles the series injected voltage. Due to the satisfactory performance in compensating all voltage and current PQ problems, UPQC becomes one of the most attractive schemes [9].

Researchers have considered about minimizing the total VA loadings of the UPQC system using different approaches [10]-[17]. In [10]-[17], the optimization of the total VA loadings is achieved at the expense of increasing the ratings of the overall UPQC system.

Actually, the sizing aspect of the UPQC system has seldom considered the power electronic converters and transformers. In [18], the authors proposed an algorithm to minimize the two converters VA ratings of UPQC for realizing the converters maximum utilization rates. The variable displacement angle control (DAC) method is applied in [18] to optimize the online VA loadings and further to minimize the converters VA ratings. Nevertheless, the transformer VA rating will affect the converters VA rating of. In this paper, we aim at obtaining the optimal total VA rating in terms of the minimum capital cost. Both the transformer and the converters VA ratings will be considered in the two-level algorithm. The variable DAC method is also utilized in the proposed two-level algorithm. This paper is organized as follows: Section II formulates the problem of optimizing the total VA rating. The proposed two-level algorithm is presented in Section III. The controller for the designed UPQC is described in Section IV. Section V shows the simulation results based on MATLAB/SIMULINK platform. Section VI concludes this paper.

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II. PROBLEM FORMULATION

A. VA Loading Equations

Fig. 2 presents the phasor diagram of the DAC method. is the displacement angle. The rated source voltage is represented by V_S .

From Fig. 2, It can be observed will also cause a phase angle shift in the resulting load current [9]. The reason is is only depending on and the load power factor angle (∅). Based on the equations in [9], the VA loading equations of the UPQC system can be established.

The series converter voltage magnitude and VA loading are calculated as follows:

$$V_{se} = V_S \cdot \sqrt{1 - 2k\cos\delta + k^2} \tag{1}$$

$$S_{se} = V_{se} \cdot I_S' = P_L \cdot \frac{1}{k} \cdot \sqrt{1 - 2k\cos\delta + k^2} \tag{2}$$

The shunt converter VA loading is computed as

$$S_{sh} = \sqrt{{P_{sh}}^2 + {Q_{sh}}^2} \tag{3}$$

$$S_{sh} = \sqrt{{P_L}^2 \cdot \frac{1+k^2-2k\cos\delta}{k^2} + {Q_L}^2 - 2Q_L P_L \frac{\sin\delta}{k}} \tag{4}$$

Then the total UPQC VA loading is

$$S_{UPQC} = S_{se} + S_{sh} \tag{5}$$

The VA rating of the series transformer can be obtained as

$$S_{ST} = \max(V_{se}) \cdot I_S / k_{min} \tag{6}$$

where $\max(V_{se})$ is the maximum series voltage and I_S/k_{min} is the maximum winding current.

B. Objective Functions and Constraints

In this work, the UPQC system VA ratings should be optimized. The transformer and converters VA ratings are two different criterions. It is often called the multi-criterion optimization problem. Roughly speaking, both of them should be small. However, the transformer and the converters VA ratings cannot simply be added together. The operating logic of the system is the VA loading cannot overtop the VA rating. Using the VA loading equations and the operating logic, the multi-criterion optimization problem is formulated as

where X, Y, and Z are the series converter, shunt converter, and transformer VA ratings, respectively. (8) and (9) are the inequality constraints, which guarantee the operating logic is satisfied. The equality constraint (10) is the expression of the series transformer VA rating. We assume the set of all achievable objective values is

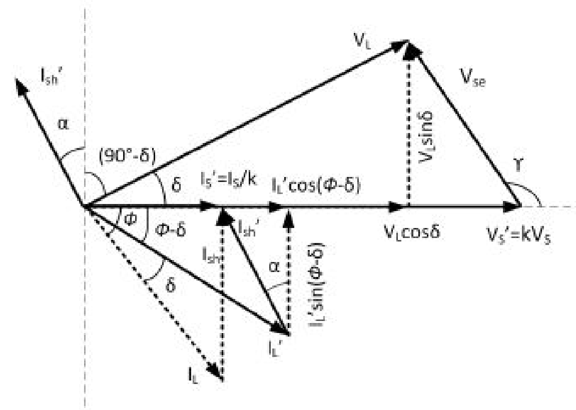


Fig. 2. Phasor diagram of DAC [9]

$$\begin{aligned} \text{minimize} \quad & F = (X+Y, Z) && (7) \\ \text{subject to} \quad & S_{se}(k,\delta) \le X && (8) \\ & S_{sh}(k,\delta) \le Y && (9) \\ & S_{ST}(k,\delta) = Z && (10) \end{aligned}$$

$$\partial = \{F(X,Y,Z) \mid X, Y, Z \text{ feasible}\} \tag{11}$$

The physical meanings of the weights are the converter and transformer unit costs. We rewrite the objective function (7) as

$$\text{minimize} \quad \lambda^T F = \lambda_{in} \times (X+Y) + \lambda_{tr} \times Z \tag{12}$$

C. Search Strategy

A two-level algorithm is utilized to solve the optimization problem in this work. In the first level, we calculate the multiple Pareto optimal values for VA rating. In the second level, the calculated Pareto optimal values are utilized to obtain the minimum total capital cost of the system.. If certain values are set for (X,Y), the transformer VA rating can be determined by solving the optimization problem as follows:

$$\begin{aligned} \text{minimize} \quad & Z = S_{ST}(k,\delta) && (13) \\ \text{subject to} \quad & S_{se}(k,\delta) \le X && (14) \\ & S_{sh}(k,\delta) \le Y && (15) \end{aligned}$$

According to (6), we write the objective function (13) as

$$\text{minimize } Z = \max_{k \in [k_{\min}, k_{\max}]} (V_{se}(k,\delta)) \cdot \frac{I_S}{k_{\min}} \tag{16}$$

Take the second derivative of V_{se} with respect to k,

$$\frac{\partial^2 V_{se}}{\partial k^2} = V_S \cdot \left(1 + k^2 - 2k\cos\delta\right)^{-\frac{1}{2}} \cdot \frac{1-\cos^2\delta}{(k-\cos\delta)^2 + \sin^2\delta} \tag{17}$$

The safe operation of the system is guaranteed by the worst-case scenario consideration. We rewrite the objective function (16) as

$$\text{minimize} \quad Z = \max(V_{se}(k_{\min}, \delta), V_{se}(k_{\max}, \delta)) \cdot \frac{I_S}{k_{\min}} \qquad (18)$$

The optimization problem can further be transformed into two parts

$$\text{minimize} \quad Z_1 = V_{se}(k_{\min}, \delta_1) \cdot \frac{I_S}{k_{\min}} \qquad (19)$$

$$\text{subject to} \quad S_{se}(k_{\min}, \delta_1) \le X \qquad (20)$$

$$S_{sh}(k_{\min}, \delta_1) \le Y \qquad (21)$$

$$\& \quad \text{minimize} \quad Z_2 = V_{se}(k_{\max}, \delta_2) \cdot \frac{I_S}{k_{\min}} \qquad (22)$$

$$\text{subject to} \quad S_{se}(k_{\max}, \delta_2) \le X \qquad (23)$$

$$S_{sh}(k_{\max}, \delta_2) \le Y \qquad (24)$$

The optimal value of is the maximum value out of and . As all constraints are satisfied, (X,Y,Z) is a Pareto optimal point. A physical interpretation is used to find the Pareto optimal point by considering the benchmark in [18].

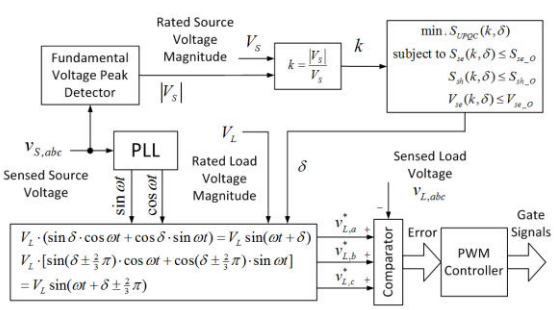
III. CONTROLLER DESIGN

A.Shunt Converter Control

Fig. 6 shows the block diagram for the reference load voltage signal generation for the designed UPQC. Firstly, calculate the fundamental peak value of the sensed source voltage , to obtain the source voltage magnitude |VS |. Then divide | VS| by the rated value of the source voltage to obtain the compensation requirement . For a certain compensation requirement , a corresponding can be obtained using the online VA loading optimization technique as

$$\text{minimize} \quad S_{UPQC}(k, \delta) \qquad (25)$$

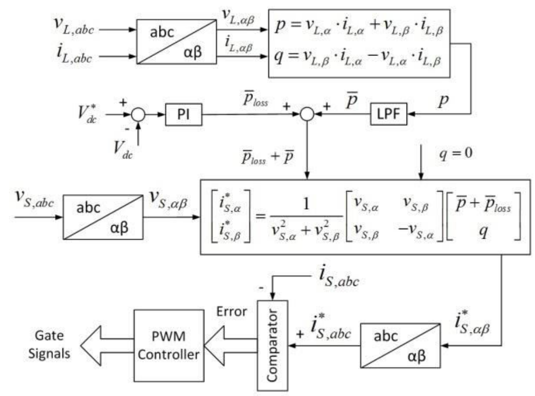
$$\text{subject to} \quad S_{se}(k, \delta) \le S_{se\_O} \qquad (26)$$



Shunt converter control.

B.Series Converter Control

The generation of the reference source current is realized by applying the p-q theory [19]. Unlike the conventional p-q theory, the reference source current is generated rather than the shunt compensation current. The sensedV_{LABC} and i_{LABC} , is processed using the abc to αβ transformation. The instantaneous load active power *p* is calculated based on$V_{l\alpha\beta}$,

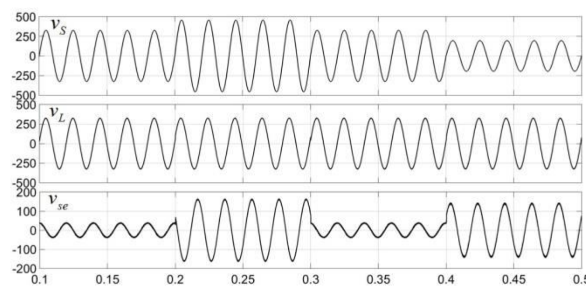


Series converter control.

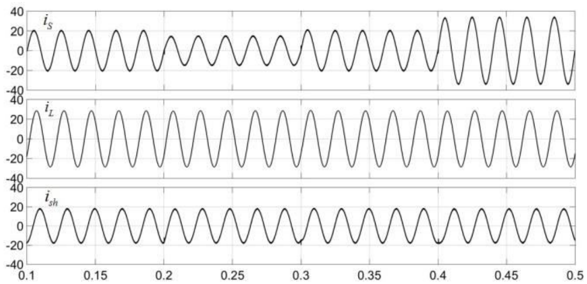
and ,. The fundamental component can p is tracked by the low pass filter (LPF) from *p*. The power losses used to maintain the dc-link voltage are generated by the proportional integral (PI) controller using the error between the reference and measured voltages of the dc-link capacitor.

IV. SIMULATION RESULTS

To verify the proposed UPQC system, the simulation is conducted. The simulation results are illustrated in Figs.

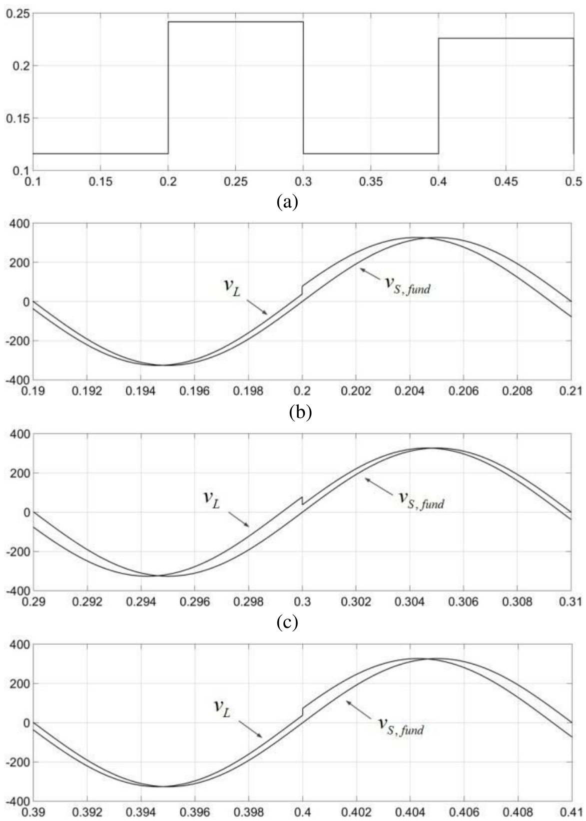


(a)



(b)

Simulation results of the designed UPQC (a) , , and , (b) , , and .



(a) (b) (c) (d)

Simulation results of the designed UPQC (a) δ (rad) during t = 0.1 s – 0.5 s, δ changes at (b) t = 0.2 s, (c) t = 0.3 s, and (d) t = 0.4 s.

V. CONCLUSION

A two-level algorithm has been utilized to minimize the capital cost of the UPQC system. In the proposed algorithm, the optimal VA ratings of the transformer and the series/shunt converter can be determined. The designed UPQC systems are compared with other topologies based systems. The corresponding controllers have been developed for the designed systems. The advantages of the two-level algorithm and controller are outlined.

*1)*Both the transformer VA rating and capital cost are involved in the two-level algorithm, which can increase the level of completeness and accuracy of the optimization. *2)*The two-level algorithm is able to be utilized in other UPQC approaches, e.g., multilevel UPQC, UPQC-DG, etc.

*3)*The safe operation of the designed system can be guaranteed by the proposed controller.

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