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Universal Custom Power Conditioner (UCPC) In Distribution Networks

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Abstract - In this paper, a general powerful circuit of a universal custom power conditioner (UCPC), which is used to improve power reliability and quality applied to distribution networks, is presented in detail. UCPC is based on series and shunt tri-level PWM converters with a battery energy storage system (BESS) for multi-function operations such as harmonic elimination, reactive power control, voltage sags compensation and uninterruptible power supply (UPS). The basic algorithm of system is deadbeat control with repetitive compensation strategy based on voltage space vector PWM method. Some simulation results are use to verify that UCPC can synthetically fulfill different compensation functions.

I. INTRODUCTION

Since Dr. N.G Hingorani presented the concept of custom power [1], more and more attentions have been paid to the power reliability and power quality in distribution system [4]-[5]. In recent years, both industrial and commercial customers of utilities have reported a rising tide of misadventure relation to power reliability and power quality. Power supply reliability is affected by such disturbances as an outage or voltage sag while power quality is affected by such phenomena as harmonics, impulses and swells. The corresponding control strategies for power supply reliability, flicker, voltage fluctuation, harmonics, asymmetrical operation and power supply interruption, are needed to be solved. For the past years, all the above described problems are investigated individually and independently, for example, the development of switching capacitors, static VAR compensator (SVC), Statcon, active power filter [3], etc. Although these have become important means to reduce and compensate those issues in power system, they have the same technical problems such as frequency detecting, fast control and protection problems asymmetrical fault occurring in the 3-phase network. Since these devices are only designed for their specific issue, they cannot synthetically improve the power quality reliability [5]. Furthermore, their cost and performance can't often satisfy the user requirement.

In the mean time, various active power filters (APF) for harmonic isolation, damping and elimination made their appearance in practical application more than 15 years [9]. However, it has been wrongly believed that parallel type of APF is an ideal harmonic compensator whose compensation characteristics would not be influenced by the source impedance. Especially when it applies to nonlinear loads that are voltage–source type of harmonic source such as diode rectifiers with direct smoothing dc capacitors [3], the series active filter is better suited for compensation instead of the parallel active filter. In some cases, a combined system of parallel and series active filter may be necessary to meet various demands of general-purpose compensation [4]. Moreover, with an increasing emphasis on power quality, the unified power flow controller (UPFC) is also being investigated for harmonic isolator applied to transmission system. On the other hand, a battery energy storage system (BESS) has proved the capability of shifting system load from daily peaks to lows, and the multipurpose applications [8]. A large capacity BESS can be located near the load center with a few hours ability to supply the demand with system damping.

In this paper, a general powerful circuit of a universal custom power conditioner (UCPC) which is applied to distribution networks is proposed. The UCPC is based on series and shunt tri-level PWM converters with a battery energy storage system (BESS). The goal of UCPC utilizing

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the energy storage battery is to achieve synthetic compensation functions, such as: short time uninterruptible power supply (UPS), reactive power compensation, harmonic damping or isolating, unbalance control, user terminal voltage fluctuation control, flicker elimination and active power storage control in one device. Because the UCPC system has a unified standard controller based on general DSP control algorithm, it can fulfil different compensation functions depended on the present supply condition and load condition at the same time. The proposed UCPC is quite different from the unified power flow controller (UPFC) [2] and the unified power quality conditioner (UPQC) [4]. UPFC requires a large amount of power rating for power flow control of transmission line. And UPQC, which is just a combined system of parallel and series active filter without a BESS system, is focused on the power quality control applied for both transmission and distribution system. Thus they are not suitable for both high voltage-power level and low voltage-power level. For the distribution networks, the power switch devices such as IGBT has more superiority over GTO because IGBT can switch at high frequency and control easily. For example, a 2-5 MVA/MW IGBT tri-level converter, it is big enough for compensation rating at a substation without using series connection method. Moreover, it has high frequency band width and fast dynamic response capability.

For limitation of length of paper, only the concept of the UCPC applied to both utility-side and load-side applications has been proposed in detail. Moreover, the basic control strategy is deadbeat control based on voltage space vector PWM method. The concept of UCPC and its control scheme are verified by some of computer simulation results.

II. INSTANTANEOUS POWERS IN THREE PHASE NETWORKS

Define Matrix [C] is the transformation of a-b-c frames into $\alpha-\beta$-0 frames: [6]

$$[C]=\sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix}=\begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

Where v_α, v_β, v_0 and i_α, i_β, i_0 are the $\alpha-\beta$-0 transformation of v_a, v_b, v_c and i_a, i_b, i_c respectively. Then Equation (3) can be decomposed by d.c. component and a.c. harmonic components, which consist of negative sequence component and harmonic component.

$$\begin{cases} p = \overline{p} + \widetilde{p} \\ q = \overline{q} + \widetilde{q} \\ p_0 = \overline{p_0} + \widetilde{p}_0 \end{cases} \tag{4}$$

Because the zero sequence power p_0 never produces a constant d.c. component without its associated a.c. component, the UCPC should compensate fully power p_0 when it applied to a three-phase four-wire networks, and the additional active power component drawn from supply needs to be injected.

$$\begin{cases} p_{control} = p_0 + \widetilde{p} \\ q_{control} = \overline{q} + \widetilde{q} \end{cases} \tag{5}$$

If shunt converter is used simultaneously for reactive, negative and harmonic component compensation, the $\alpha-\beta$ axis current reference is given by Equation (6):

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix}=\frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} -p_{control} \\ -q_{control} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} -i_0 \\ i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \tag{7}$$

When the tri-level series converter of UCPC is used simultaneously for reactive, negative and harmonic component compensation, the $\alpha-\beta$ axis voltage references is given by Equation (8):

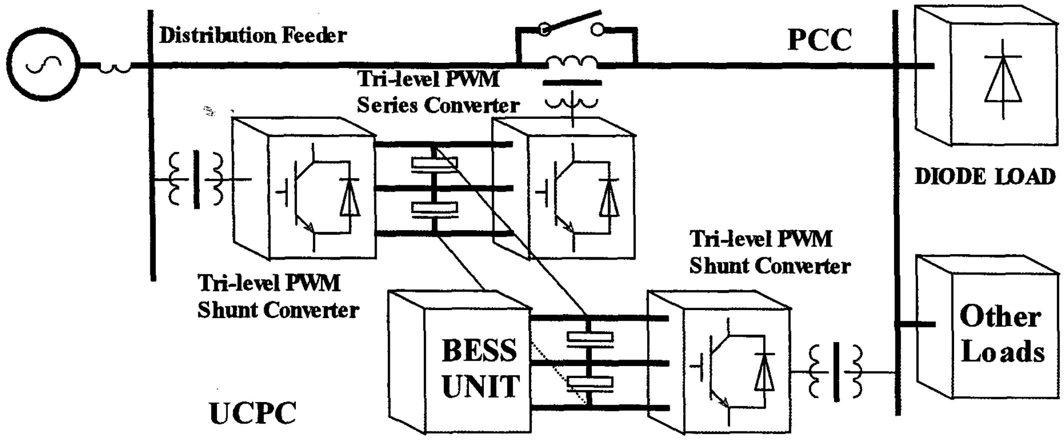

Figure 1: The main circuit topology of UCPC

$$\begin{bmatrix} v_{c\alpha}^{*} \\ v_{c\beta}^{*} \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} -p_{control} \\ -q_{control} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} v_{ca}^{*} \\ v_{cb}^{*} \\ v_{cc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} -v_0 \\ v_{c\alpha}^{*} \\ v_{c\beta}^{*} \end{bmatrix} \tag{9}$$

When the tri-level converter of UCPC is used for the charge control of battery or UPS function, the active-reactive power control is becoming the main issue, and UCPC system still satisfy the compensation demands of load such as negative and harmonic compensation. Then the $\alpha-\beta$ axis current reference is given by Equation (10):

$$\begin{bmatrix} i_{c\alpha}^{*} \\ i_{c\beta}^{*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_{control} + \bar{p} \\ q_{control} \end{bmatrix} \tag{10}$$

Generally, control parameters are up to the application purposes of tri-level PWM converter shown in Table 1.

TABLE 1

APPLICATION PURPOSES AND CONTROL PARAMETERS

APPLICATION PURPOSES	CONTOL PARAMETERS
Sags and swell control	$p_{control} = \bar{p}$; $q_{control} = \bar{q}$
Uninterrupted power supply	$p_{control} = p_0 + \bar{p} + \tilde{p}$; $q_{control} = \bar{q} + \tilde{q}$
Power factor control	$p_{control} = p_0 + \bar{p} + \tilde{p}$; $q_{control} = \bar{q} + \tilde{q}$
Harmonic elimination	$p_{control} = p_0 + \tilde{p}$; $q_{control} = \tilde{q}$
Reactive power compensation	$p_{control} = p_0$; $q_{control} = \bar{q}$
Flicker compensation	$p_{control} = p_0 + \tilde{p}$; $q_{control} = \bar{q} + \tilde{q}$
Unbalance component control	$p_{control} = p_0 + \tilde{p}$; $q_{control} = \bar{q} + \tilde{q}$

It also should be known that the dynamic compensation performance of UCPC is strongly influenced by the selection of high-pass filters and their characteristic parameters. This consideration will be discussed next.

III. UNIVERSAL CUSTOM POWER CONDITIONER

A. System Function and Topology of UCPC

Figure 1 shows the main circuit topology of UCPC. The main structure of tri-level shunt PWM converter is also shown in Figure 2. Since the main structure of tri-level series PWM converter has the similar characteristic of shunt one, it isn't described here. The basic functions for improvement of power reliability and power quality of UCPC are summarized as following:

Series PWM Converter:

- To compensate voltage harmonics, including negative and zero sequence components at the fundamental frequency.
- To suppress or isolate harmonic currents through the power line.
- To improve the distribution system stability or damping oscillation.
- To control the active and reactive power flow.
- Sag and swell control, flick voltage control and power factor control.

Shunt PWM Converter:

- To eliminate or absorb in current harmonics, including negative and zero sequence components at the fundamental frequency.

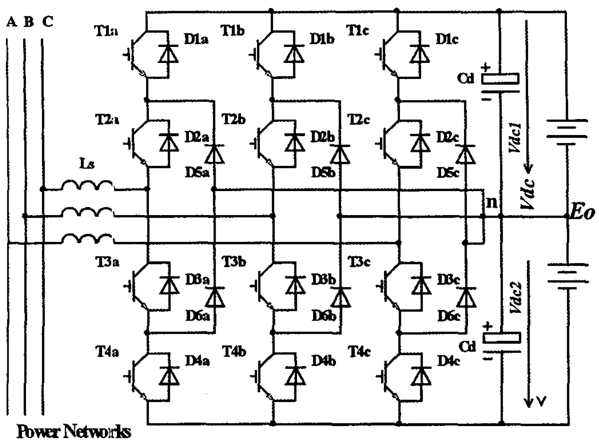

Fig. 2 The main circuit of tri-level shunt PWM converter

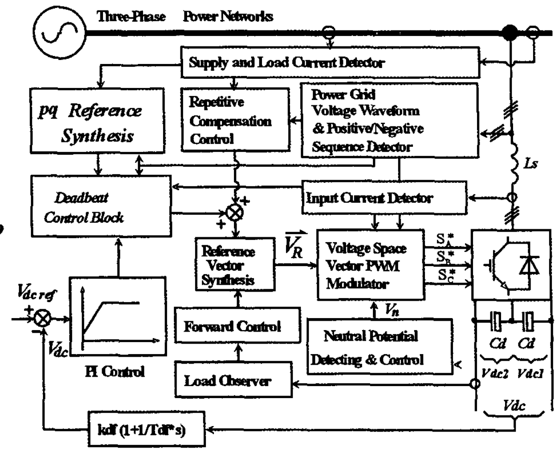

Fig. 3 The principle diagram of control system based deadbeat control with repetitive compensation strategy

- ✧ To compensate the reactive power of load.
- ✧ To regulate and control the DC link voltage.
- ✧ To maintain the terminal voltage of PCC or injection node.
- ✧ To storage and control the energy of battery, UPS and outage control.

Battery energy storage system (BESS):

- ✧ To shift system loads from daily peaks to lows.
- ✧ To be a potential standby generator.
- ✧ The whole system can select automatically the above compensation functions associated with identifying the power supply and load conditions.

B Deadbeat Control Algorithm of UCPC

The diagram of control system of shunt convert is shown in Figure 3. The control algorithms consist of two parts: upstream and downstream algorithm. The upstream one provides the high accuracy detecting of the power supply synchronous frequency, the rapid detecting of positive and negative sequence voltage and α−β axis voltage or current references calculation depended on the present supply and load conditions. The downstream one deals with regulating the dc link or battery voltage and shaping current waveform to track the references. It is realized by means of dead-beat control technology based on voltage space vector PWM method [7]. Generally, deadbeat control is a digital feedback strategy that is designed to control the pulse width so that the output of converter can track the reference at every sampling instant. Any deviation from the reference due to a load disturbance or nonlinear load is corrected with in one sampling interval Ts. From reference[10], the state equation of converter is:

$$\dot{X} = AX + BU \tag{11}$$

where

$$X=\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix}, U=\begin{bmatrix} -v_d+v_{sd} \\ -v_q+v_{sq} \end{bmatrix}, A=\begin{bmatrix} -\dfrac{R_c}{L_c} & w \\ -w & -\dfrac{R_c}{L_c} \end{bmatrix}, B=\frac{1}{L_c}$$

$$\begin{bmatrix} i_{cd}(k+1) \\ i_{cq}(k+1) \end{bmatrix} = G\begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H\begin{bmatrix} -v_d(k)+v_{sd}(k) \\ -v_q(k)+v_{sq}(k) \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} = H^{-1}G\begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H^{-1}\begin{bmatrix} i_{cd}(k+1) \\ i_{cq}(k+1) \end{bmatrix} + \begin{bmatrix} v_{sd}(k) \\ v_{sq}(k) \end{bmatrix} \tag{13}$$

where reference voltage vector $\vec{v}(k) = [v_d(k), v_q(k)]$.

Thus it could be used to shape the output of converter by means of voltage space vector PWM method. However, in the case of diode rectifier load, harmonic elimination needs the repetitive control compensation to improve the compensation effect of UCPC. This consideration will be discussed latter for the limitation of paper.

IV. SIMULATION RESULTS

To verify the proposed UCPC and its control algorithm, a digital simulation based on MATLAB and SIMULINK® environment has been accomplished. For the limitation of the length of this paper, only the simulation results of active–reactive power control and harmonic elimination with tri-level shunt converter under diode rectifier load are given. The main system parameters are Vsm=311V, f=50Hz; system inductance $Lsystem$=0.6mH. AC side of tri-level shunt converter Ls=6mH; Rs=0.5Ω; DC side Cd=4700μF; V_{dcg}=1200V. The power loss of three-phase diode rectifier load (DRL) side (resistance-inductance type) is P_{out}=15kW; sampling frequency fs=4.8kHz. The results are shown in Figure 4 to 6. In Fig.4, the reactive power of load could be compensated by the tri-level shunt converter. In Fig.5, the harmonic injected by diode rectifier load could be reduced by the common deadbeat control. But it still remains a large of harmonics. By means of repetitive compensation strategy, the periodic pulse produced by DRL can be elimination effectively. After compensation, THD of supply current is reduced from 29.42% to 4.13%. Also the dynamic response is fast. In Fig.6, the power factor control is perfected. The waveform of supply current is near sinusoidal and in phase with the supply voltage.

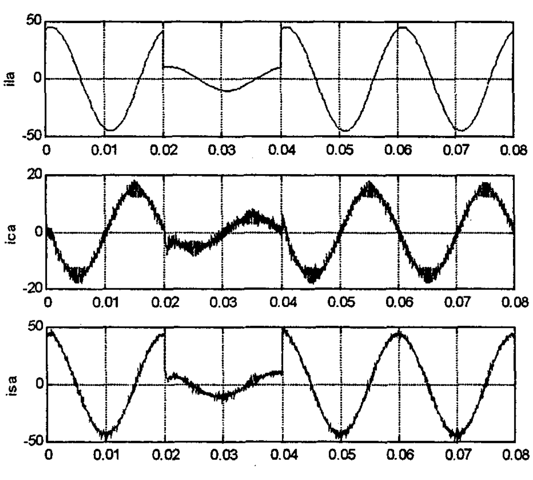

Fig. 4 Reactive Power Compensation Control

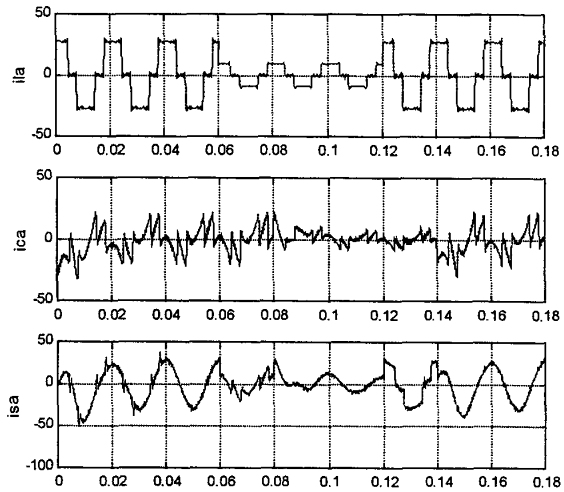

Fig. 5 Dynamic Harmonic Elimination under Rectifier Load

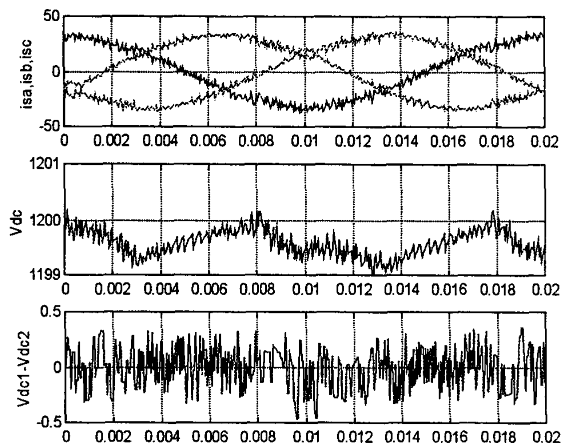

Fig. 6 Power Factor p.f.=1 Control

V. CONCLUSIONS

The proposed custom power device UCPC is a powerful tool for power reliability and power quality improvement in distribution networks due to its quick response performance and versatile compensation functions. Moreover, it integrates almost all needed compensation characteristics that can be easily realized by a single device that is made up from tri-level PWM converter with a battery energy storage system (BESS). The dead-beat control with repetitive compensation algorithm based on voltage space vector pulse width modulation (VSVPWM) method has been successfully introduced to realize the various and synthetic compensation purposes such as active power, reactive power, harmonic component and asymmetry. Some simulation results show that UCPC can synthetically fulfill different compensation functions depended on the present supply and load condition at the same time. Furthermore, the physical prototype of UCPC has been on the way of development.

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