A Unified Approach for Distribution System Conditioning: Distribution System Unified Conditioner (DS-UniCon)

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Abstract: In this paper, a unified approach to simplify the traditional distribution system compensators is proposed and investigated. Distribution System Unified Conditioner (DS-UniCon) is a unified device that combines all the individual compensators such as active filters, VAR compensators and Uniterruptible Power Supply (UPS) in order to compensate harmonics, reactive power, asymmetry, voltage variation and power supply interruption by using the state-of-art of power electronics. DS-UniCon offers a higher effective and economic means to improve power quality.

Keywords: Harmonics, Reactive Power, Unbalance, Voltage-Flicker, Power Quality, Unified Power Flow Controllers, Uniterruptible Power Supply, Var Compensators, Tri-level Converters, FACTS.

I. INTRODUCTION

Further increasing the reliability, improving the quality and reducing the costs of power supply are the main trend of the technology development of the power system control. The problems in distribution systems are even more and more severe than in the transmission systems [1]-[9]:

- voltage fluctuation and flicker, mainly caused by network faults, switching of capacitor banks and industrial loads such as welding machines and arc furnaces,
- harmonic currents and voltage resulting from low-pulse converter loads, especially diode rectifiers with capacitive smoothing,
- voltage unbalances because of unsymmetrical loading on each phases,
- interruptions of power supply because of network faults.

The above articles are the main issues as the environmental factors affecting high quality power supply.

Up to now, there are still many investigators to take different individual focal points on one of the above specialized aspects, for instance, harmonic problems, voltage flicker or power supply interruption etc. Moreover, some specialized compensators have been utilized in power system for different manners. However, not only various problems to execute different devices have the highly installation requirements and higher costs for users, but also expensive maintenance. Due to above considerations for improving power quality, the necessity to develop a unified conditioner in distribution power network or consumers becomes more and more important.

This application is to study and to acquire a unified conditioner for distribution and low or medium voltage systems, which is called Distribution System Unified Conditioner (DS-UniCon) and offers a higher effective and economic means to improve power supply quality. This device not only can compensate the above described issues but also has energy storage function. This energy storage function can reduce the peak load demand for the power system in order to ensure adequate energy supply. When the power interruption happens in a specific area, this DS-UniCon can work as an UPS (Uninterruptible Power Supply) to supply power in a very short time to guarantee power quality. But in normal operation it works as a harmonic, reactive power, voltage flicker and unbalanced compensator together to improve power factor.

Means for improvement of power supply quality are summarized in Fig.1. It can be seen that the flexibility of DS-UniCon covers all requirements by using only one single device.

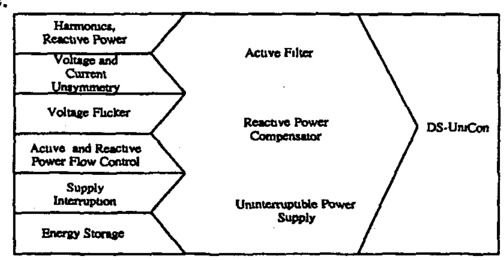

Fig. 1

To create a unified device called " DS-UniCon " is a synthesis of all the problems of individual devices together: unbalanced operation, flicker, protection, frequency fluctuation, battery charger and harmonics etc., as all of them may happen in a very short time or under steady-state condition. By the state-of-art of power electronics, determination of a suitable and reasonable method to detect the required compensating signals in dynamic response and corresponding circuit methodology are extremely important. The control strategies and physical hardware of a Distribution System Unified Conditioner (DS-UniCon) are investigated in detail in this paper. DS-UniCon is based on series and shunt Tri-level PWM converters with a Battery Energy Storage System (BESS) for multi-function operations. Control strategies are presented for dynamic compensation of reactive power, harmonics, asymmetry, charging and discharging, voltage flicker reduction control at the same time by normalization of Instantaneous Reactive Power Theory [10] [11]. The compensation problem [12][13] generated by Instantaneous Reactive Power Theory, which will generate oscillation in compensated current when the 3-phase voltage is asymmetry or with harmonics, can be eliminated by normalization technique. Hardware consideration of DS-UniCon is also presented in this paper. Due to the consideration of life cycle of battery system and converter's operation, the structure of DS-UniCon with two shunt Tri-level converter and one series Tri-level converter is proposed ,and the control algorithm of DS-UniCon is addressed with the charging and discharging processes in addition to integrated compensation strategy such that this device can compensate harmonics, reactive power, asymmetry, reducing the voltage flicker, charging or discharging the battery at the same time.

II. BASIC SCHEME OF DS-UniCon

The first testing model of DS-UniCon should have the following key blocks:

1. 3-level IGBT Converters with Snubber Circuit,
2. D.S.P. Based Pulse Generator,
3. Fast Measuring System,
4. Fast Controller with fine control strategy,
5. Industrial PC, and
6. Protection System.

The DS-UniCon is placed between the power source and the load in order to minimize the loss and to improve the power quality. However, the instantaneous information of DS-UniCon and the loads are needed to know by taking the data from the measuring system. A digital signal processor is used to control all the required functions of the DS-UniCon by triggering the pulse output broad and driving circuit to control the converters. Protection system is needed to ensure the safety operation. There are mainly two operational purposes for industrial PC : One is to monitor the whole operation of DS-UniCon and power network , and second is to send commands to D.S.P. in order to adopt the working process.

Fig.2 shows the basic circuit configuration of the Distribution System Unified Conditioner. There are 3 converters. One is connected in series and the other two are connected in parallel. Tri-level converters are chosen to apply into distribution system with higher voltage capability. Battery Energy Storage System (BESS) and capacitors are linked with converters for multi-function operations such as the active filter, active and energy storage control, unbalance compensation, etc.

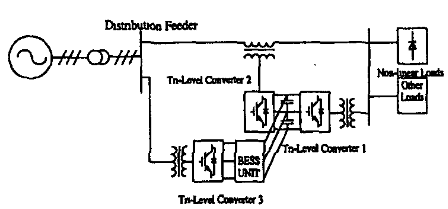

Fig. 2

III. INSTANTANEOUS POWER FLOW OF Ds-UniCon

The instantaneous p-q theory is under investigation as the p-q definition making the real-time detection and compensation are possible.

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

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

Equations (1) and (2) are the transformation between the a-b-c frames and $\alpha-\beta$ frames.

$$[P] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (3)$$

$$[P^{-1}] = \sqrt{\frac{3}{2}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \quad (4)$$

Matrix [P] is the transformation of a-b-c frames into $\alpha-\beta$ frames, matrix $[P^{-1}]$ is the inverse transformation of [P].

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

Equation (5) is the instantaneous real power (p), instantaneous imaginary power (q) and instantaneous zero power (p_0).

The instantaneous average part of real power (6) is :

$$\bar{p} = \sum_{n=1}^{\infty} 3V_{+n} I_{+n} \cos(\phi_{V+n} - \phi_{I+n}) + \sum_{n=1}^{\infty} 3V_{-n} I_{-n} \cos(\phi_{V-n} - \phi_{I-n}) \quad (6)$$

The instantaneous alternating part of real power (7) is:

$$\begin{aligned} \tilde{p} = &\left\{ \sum_{n=1}^{\infty} -3V_{+n} I_{-n} \cos(2\omega_n t + \phi_{V+n} + \phi_{I-n}) \right\} \\ &+ \sum_{n=1}^{\infty} -3V_{-n} I_{+n} \cos(2\omega_n t + \phi_{V-n} + \phi_{I+n}) \\ &+ \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \left[\sum_{n=1}^{\infty} 3V_{+m} I_{+n} \cos((\omega_m - \omega_n)t + \phi_{V+m} - \phi_{I+n}) \right] \\ &+ \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \left[\sum_{n=1}^{\infty} 3V_{-m} I_{-n} \cos((\omega_m - \omega_n)t + \phi_{V-m} - \phi_{I-n}) \right] \\ &+ \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \left[\sum_{n=1}^{\infty} -3V_{+m} I_{-n} \cos((\omega_m + \omega_n)t + \phi_{V+m} + \phi_{I-n}) \right] \\ &+ \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \left[\sum_{n=1}^{\infty} -3V_{-m} I_{+n} \cos((\omega_m + \omega_n)t + \phi_{V-m} + \phi_{I+n}) \right] \end{aligned} \quad (7)$$

The instantaneous average part of imaginary power (8) is:

$$\begin{aligned} \bar{q} = &\sum_{n=1}^{\infty} -3V_{+n} I_{+n} \sin(\phi_{V+n} - \phi_{I+n}) \\ &+ \sum_{n=1}^{\infty} 3V_{-n} I_{-n} \sin(\phi_{V-n} - \phi_{I-n}) \end{aligned} \quad (8)$$

The instantaneous alternating part of imaginary power (9) is:

$$\tilde{q} = \Bigg\{ \sum_{n=1}^{\infty} -3V_{+n}I_{-n}\sin\left(2\omega_n t + \phi_{V_{+n}} + \phi_{I_{-n}}\right)$$

$$+ \sum_{n=1}^{\infty} -3V_{-n}I_{+n}\sin\left(2\omega_n t + \phi_{V_{-n}} + \phi_{I_{+n}}\right) \tag{9}$$

$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{+m}I_{+n}\sin\left((\omega_m - \omega_n)t + \phi_{V_{+m}} - \phi_{I_{+n}}\right)\right]$$

$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} 3V_{-m}I_{-n}\sin\left((\omega_m - \omega_n)t + \phi_{V_{-m}} - \phi_{I_{-n}}\right)\right]$$

$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{+m}I_{-n}\sin\left((\omega_m + \omega_n)t + \phi_{V_{+m}} + \phi_{I_{-n}}\right)\right]$$

$$+ \sum_{\substack{m=1\\ m\neq n}}^{\infty}\left[\sum_{n=1}^{\infty} -3V_{-m}I_{+n}\sin\left((\omega_m + \omega_n)t + \phi_{V_{-m}} + \phi_{I_{+n}}\right)\right]$$

It is obvious that average part of the instantaneous real power is the active power from equation (6) and is composed with fundamental one, harmonic components and imbalance. It will be the same case for the reactive power such as the average part of instantaneous imaginary power (8). The oscillating parts of instantaneous real (7) and imaginary (9) power together form the harmonic power vectors.

A. Instantaneous Power Flow of DS-UniCon on Unified Power Quality Conditioner (UPQC)

The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics. Fig. 4 shows the general configuration of UPQC.

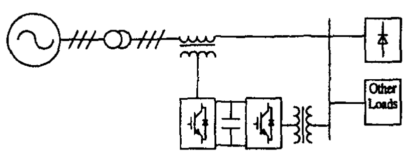

Fig. 4 (General UPQC)

The chief aim of series-active filter is harmonic isolation between a sub-transmission system and a distribution system. In addition, it has the capability of voltage-flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling. The main purpose of the shunt-active filter is to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc-link voltage between both active filters.

According to Fig. 5, the dc-link voltage v_c is the sum of fluctuating component $\tilde{v}_c$ so that the dc-link voltage in UPQC is given by

$$\tilde{v}_c = \frac{1}{C}\int \frac{\Delta p}{v_c}\,dt = \frac{1}{C}\int \frac{p_{SAF} + p_{PAF}}{v_c}\,dt, \tag{10}$$

, where p_{SAF} and p_{PAF} are the absorbed or injected instantaneous active power which is composed of voltage flicker, imbalance and harmonics by the series-active filter and shunt-active filter respectively so that the voltage of dc-link capacitor may fluctuate. Releasing energy from shunt converter is not suggested as the current will pass through the series converter and voltage variation will happen in the series converter, Δv_s. Fig. 5 shows the instantaneous power flow.

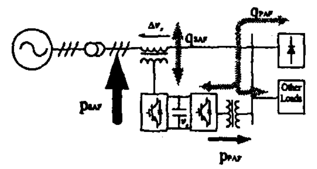

Fig. 5

In Fig.6, it shows the dc-link voltage regulation. One more shunt converter is applied to the circuit in order to keep the dc-link voltage to be constant. However, when the voltage flicker and imbalance is happened in a short time, a larger capacitor can be employed to reduce the dc-link voltage fluctuation. But, for long-term overvoltage/undervoltage, one more converter is needed. Also, it (left side converter in Fig. 6) may work as a power source to supply the power for harmonics, voltage flicker and imbalance compensation.

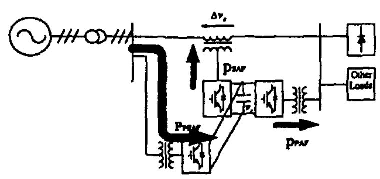

Fig.6 (DC-Link Voltage Regulation)

B. Power Flow Consideration of DS-UniCon on Uninterruptible Power Supplies (UPS)

Uninterruptible Power Supplies are designed to supply clean and uninterrupted power to equipment. The Ds-UniCon can also supply power in a short peak load period. The Lead-Acid Batteries are employed for the Battery Energy Storage System (BESS).

B.1 Power Source Supply Interruption

Fig. 7 shows the instantaneous power flow of DS-UniCon instead of the operation of UPS. Power will be given by BESS inside the DS-UniCon and the compensation action is still operating at the same time.

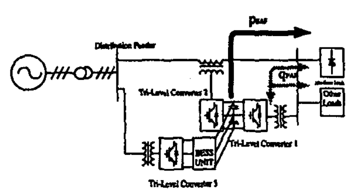

Fig. 7

B.2 Peak-Load Period

One part of the load power can be supply by BESS of DS-UniCon during peak load period. Fig. 8 shows the instantaneous power flow during peak load.

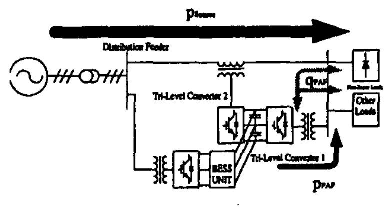

Fig. 8

B.3 Battery Life-Cycle Protection

There are two main factors to influence the battery life-cycle: one is the over-discharging and the other is the over-charging. The main purpose of converter 3 (Left converter in Fig. 2) for BESS is to prolong the operation life of batteries and to ensure the voltage balance among the batteries.

C. Operation Tasks of Converters

Table 1 summaries the operation of converters of DS-UniCon.

Converter 1 (Shunt connected converter near load)	Converter 2 (Series Connected converter)	Converter 3 (Shunt Connected Converter near source)
Harmonic Current	Voltage Flicker/Fluctuation	DC-Link Voltage Regulator
Reactive Current	Voltage Imbalance	Active Power Supply Path for the other compensators
Imbalance Current	Voltage Harmonics	Batteries Charging/ Discharging Balancing
Peak-Load Current Supply	Voltage Supply as UPS	Battery Overcharging and Undercharging Protector

Table 1

IV. NORMAILIZATION OF INSTANTANEOUS POWER CONTROL STRATEGY

A. Compensation Issues on Application of Instantaneous Power

It is assumed that the balance voltage without harmonics is given so that the instantaneous p-q compensation strategy can be achieved to compensate the harmonics, reactive power and imbalance. The equation (11) shows the detected fundamental component by instantaneous p-q theory through a low-pass filter.

$$\begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} = \frac{1}{v^2}\left(\sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix}\right) = \begin{bmatrix} \sqrt{2}I_1 \sin(\omega t + \phi_1) \\ \sqrt{2}I_1 \sin(\omega t - \frac{2\pi}{3} + \phi_1) \\ \sqrt{2}I_1 \sin(\omega t + \frac{2\pi}{3} + \phi_1) \end{bmatrix} \quad (11)$$

However, when the voltage is in unbalance or with harmonics, the error will be generated and is given in (12).

$$\begin{bmatrix} \Delta i_{a1} \\ \Delta i_{b1} \\ \Delta i_{c1} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\left(\begin{bmatrix} v_{\alpha h}\frac{\bar{p}}{v^2} + v_{\beta h}\frac{\bar{q}}{v^2} \\ v_{\beta h}\frac{\bar{p}}{v^2} - v_{\alpha h}\frac{\bar{q}}{v^2} \end{bmatrix} + \begin{bmatrix} v_{\alpha f}(\frac{\bar{p}}{v^2} - \frac{I_1\cos\phi_1}{E_1}) + v_{\beta f}[\frac{\bar{q}}{v^2} - \frac{I_1\sin(-\phi_1)}{E_1}] \\ v_{\beta f}(\frac{\bar{p}}{v^2} - \frac{I_1\cos\phi_1}{E_1}) + v_{\alpha f}[\frac{\bar{q}}{v^2} - \frac{I_1\sin(-\phi_1)}{E_1}] \end{bmatrix}\right) \quad (12)$$

When a system is considered under the asymmetric voltage and current without harmonics. The third harmonic component is generated in compensated line current. There is a main reason to generate this third harmonic.

- Third harmonic will also be created by the term "$v_\alpha^2 + v_\beta^2$" which is not constant in imbalance.

Recently, there are some methods to eliminate the 3rd harmonic component generation by using instantaneous p-q control strategy such as [11][12].

$$I_{Fa} = \left\{\left(\frac{1}{\pi}\int_{\theta_{a-1\pi}}^{\theta_a} i_{Fa}\cos\theta_a d\theta_a\right)^2 + \left(\frac{1}{\pi}\int_{\theta_{a-1\pi}}^{\theta_a} i_{Fa}\sin\theta_a d\theta_a\right)^2\right\}^{\frac{1}{2}} \quad (13)$$

Equations (13) from [11] and (14) from [12] are the control

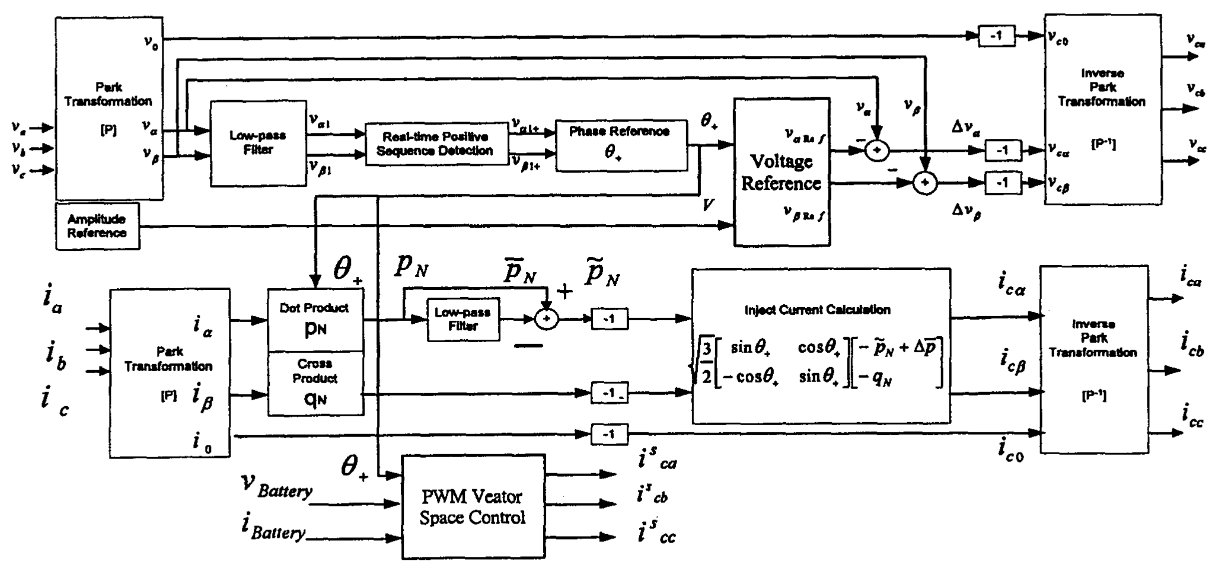

Fig. 9

strategies to block the 3rd harmonic generation in line current while voltage and current are both asymmetric.

$$\psi_0 = \frac{\int_0^T p dt}{\int_0^T (v_a^2 + v_b^2 + v_c^2) dt} \qquad (14)$$

Although the system performance can be improved, the dynamic response of those systems is limited by using average methods with integration.

B. Normalization of Instantaneous Power

The normalized technique, $v_\alpha^2 + v_\beta^2 = 1$, is taken to eliminate the oscillation due to variation of voltage.

$$p_N = \sqrt{\frac{3}{2}}(i_\alpha \sin\phi_+ - i_\beta \cos\phi_+) \qquad (15)$$

$$q_N = \sqrt{\frac{3}{2}}(i_\beta \sin\phi_+ + i_\alpha \cos\phi_+) \qquad (16)$$

Real-time positive sequence detection method (17) (18) is employed so that the suitable reference signal is given according to equation (19), where $V_{ref.}$ is given according to the system requirement.

$$v_{\alpha+} = \frac{1}{2}v_\alpha + \frac{1}{2\omega}\frac{dv_\beta}{dt} \qquad (17)$$

$$v_{\beta+} = \frac{1}{2}v_\beta - \frac{1}{2\omega}\frac{dv_\alpha}{dt} \qquad (18)$$

$$v_{ref.} = |V_{ref.}| \angle \left(\tan^{-1}\left(\frac{v_{\beta+}}{v_{\alpha+}}\right) \right) \qquad (19)$$

Control strategy is presented in Fig. 9 and the upper-part of this control diagram shows the technique of getting the phasor synchronization information from the voltage data. According to equations (15) and (16) instantaneous normalized real and imaginary power can be obtained without the voltage effect so that this device can compensate the voltage variation, harmonics, imbalance, reactive power and storage action at the same time. However, the device parameters and driving scheme for IGBT's have to be considered. The Advanced Deadbeat Algorithm and Vector Space PWM Control are employed.

V. SIMULARTION RESULTS

The main system parameters are Vsm=311V, f=50Hz; AC side Ls=6mH; Rs=0.5Ω; DC side Cd=4700μF; Ro=45Ω, Lo=3mH; V_{dcg}=800V, P_{out}=15kW; sampling frequency fs=4.8kHz. The inner loop will be designed to achieve dead-beat control of the input currents and the outer loop of control system is used to regulate the DC voltage based on PI control. The results are shown in Figure 10, 11, 12 and 13.Figure 10 shows the dynamic response to load step and it shows the compensated source current, voltage variation in dc-link capacitor and upper voltage and lower voltage of a Tri-level converter. Fig. 12 shows the dynamic harmonic compensation in current, the upper waveform is the non-linear load current, the second waveform is the injected current and the last one is the current after compensation. Fig. 13 shows the voltage sag operation.

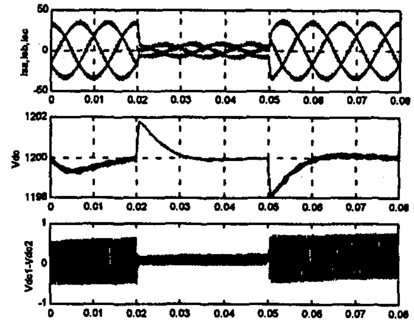

Figure10: Dynamic response to load step

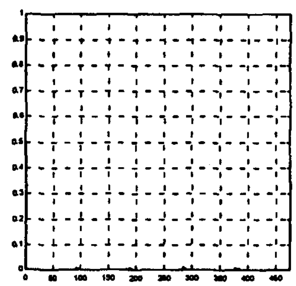

Fig.11 (Spectrum of Supply Current)

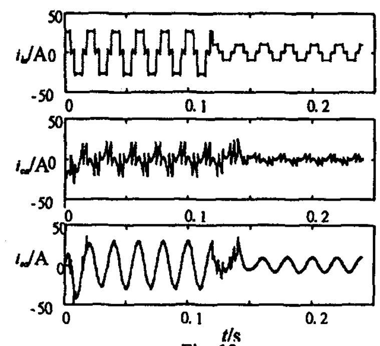

Fig. 12

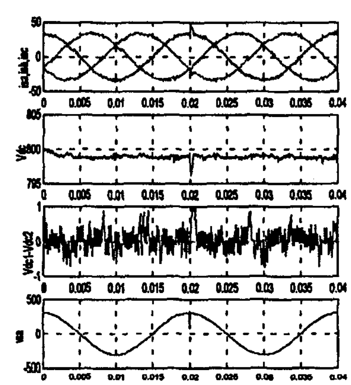

Fig. 13

VI. CONCLUSION

The concept of a unified approach for distribution system conditioning device is proposed and called Distribution System Unified Conditioner (DS-UniCon). The first model and scheme of DS-UniCon is investigated and proposed. According to the power flow consideration, batteries balancing and over-charging or over-discharging protection of BESS, two-shunt and one-series converters, which are the Tri-level converters to ensure the voltage capacity in low or medium distribution system, are constructed to form the DS-UniCon device. Normalization of instantaneous real and imaginary power is employed to reduce the error generated by instantaneous p-q theory directly. Integrated compensation strategy is combined of normalization of instantaneous power, Advanced Deadbeat Algorithm and Vector Space PWM Control together. The simulation results show the validity of this approach.

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VIII. BIOGRAPIES

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