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Fuzzy Logic Controller Based High Frequency Link AC-AC Converter For Voltage Compensation Using SPWM Technique

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Abstract—In this paper, an advanced high frequency link AC-AC Push-pull cycloconverter for the voltage compensation is proposed in order to maintain the power quality in electric grid. The proposed methodology can be achieve arbitrary output voltage without using large energy storage elements. So that the system is more steadfast and less costly compared with the conventional inverter topology. Additionally, the proposed converter does not contain any line frequency transformer, which reduces the cost further. The control scheme for the push pull cycloconverter employs the fuzzy logic controller based sinusoidal pulse width modulation (SPWM) to accomplish better performance on voltage compensation, like unbalanced voltage harmonics elimination. The simulation results are given to show the effectiveness of the proposed high frequency link AC-AC converter and fuzzy logic controller based SPWM technology

Index Terms — Push-Pull cycloconverter, Fuzzy logic controller (FC) and sinusoidal pulse width modulation (SPWM).

1 Introduction

As the rapid increasing of the number of the non-linear loads installed in modern grid, it becomes a big concern to maintain the power quality within the acceptable limits [1]. The developing of the concept of microgrid makes this requirement even crucial because that the microgrid is much weaker than the conventional grid and thus easier to be troubled [2-3]. Most of the developed solutions to maintain the power quality are qualified to choose the inverter-based converters [4]. Deplorably, the large passive storage components like electrolytic capacitors, which unavoidably exist in the inverter-type converters, not only decrease the reliability of the equipment, but also increases the cost. Alternative approaches are proposed based on single-phase AC-AC topologies or matrix converters [5].

The standards-compliant inverters [6], which are principally designed for operation with the wider electricity network, face fundamentally different operating conditions in the confines of an isolated microgrid. These inverters are a key enabling technology of distributed generation in general and of renewables in particular, their operation in an isolated microgrid is a concern. Though, the matrix based solutions requires complex structures and control algorithms which make them difficult to handle especially during the fault condition.

While the single-phase based solutions mainly focus on dealing with the fundamental voltage quality issue such as reactive power variation or voltage sag etc. Harmonics problems are ignored due to the natural limitation of the single-phase circuit [7]. Recently, a new concept in the direct AC-AC power conversion field is proposed [8] which applies the Dual Virtual Quadrature Sources (DVQS) voltage synthesis theory to the traditional AC-AC choppers to achieve the required voltage output. Additionally, only the balanced grid harmonics are concerned in all the circumstances. An improved method for unbalanced voltage harmonics elimination is still mandatory. The goal of the advanced High Frequency Link AC-AC Converter [9-11] is to apprehend high frequency power conversion at the same time to achieve galvanic isolation by using a high-frequency transformer. By applying the Fuzzy logic controller based sinusoidal pulse width modulation to this type of single-phase converter, a series of high power density converter for grid voltage compensation can be obtained.

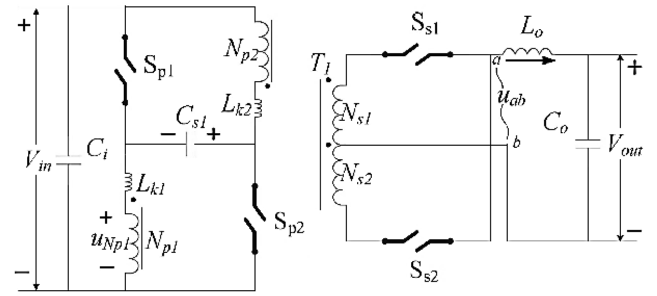
In this paper, an Advanced High Frequency Link (AHFL) AC-AC converter for voltage compensation is proposed. The AHFL converter can attain arbitrary voltage output without using any large electrolytic capacitors. Thus, the system reliability can be improved. Moreover, the converter has no line frequency transformer, which also reduces the cost. The Fuzzy logic Control (FC) scheme based on Sinusoidal Pulse Width Modulation (SPWM) technology is applied to achieve the function of unbalanced voltage harmonics elimination, which greatly improved the performance of the voltage compensation. The simulation results are given to shows the effectiveness of the proposed AHFL converter and SPWM technology.

2 Analysis Of Advanced High Frequency Link AC-AC Converter

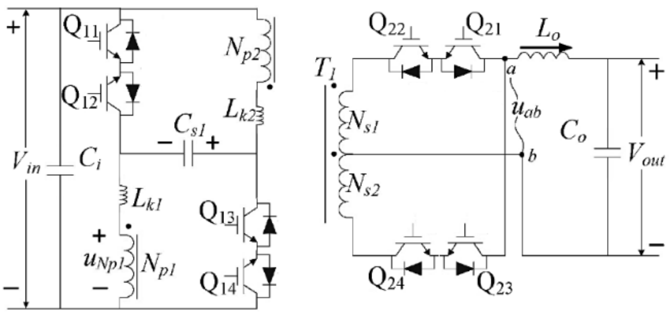
The main circuit of the AHFL AC-AC converter designed for voltage compensation is shown in Fig.l(a). The circuit can be distributed into two parts. They are,

- Input push-pull forward cycloconverter
- Output push-pull cycloconverter.

Compared with the AC-AC push-pull forward converter which is proposed and examined in [12], two additional bi-directional switches Ss1 and Ss2 are added to the secondary side circuit of the main circuit. So that , the line frequency transformer is replaced by means of new four windings transformer T_k which can now operate under the high frequency switching condition. The turns for each winding of T_k are denoted as n_{p1}, n_{p2}, n_{s1} and n_{s2} respectively whereas $n_{p1} = n_{p2}$ and $n_{s1} = n_{s2}$. The turn ratio N equals n_{p1}/ n_{s1}. Different from the circuit approached in [12], all the bi-directional switches are realized by two IGBTs connected in series which is shown in Fig.l(b). At the same time, the output LC filter L_o and C_o is moved to the secondary side to make the circuit simpler. The energy in the leakage inductors L_{k1} and L_{k2} of T_k can be recycled by adding one clamping capacitor Cs1. Associated with the circuit presented in [12], the large size of the system is reduced by employing the high frequency transformer. The proposed circuit has fewer passive components which makes the circuit even smaller and easier to analyze. There are four operational modes for the AHFL AC-AC converter circuit depending on different polarity of the input voltage V_{in} and the output voltage V_o .The demonstration of the gate signals and the crutial waveforms of the circuit for each mode are shown in Fig.2.



(a)



(b)

Fig.l Proposed AHFL AC-AC converter (a) main circuit (b) realization of bi-directional switches

In each operational mode, one switching period is divided into two stages, which are named as the positive stage and the negative stage. SPWM method is applied to each stage to decide the duty cycle of all the transistors. The duty cycle of the circuit D is defined as follows: The magnitude of D equals the total duty cycle of the SPWM voltage U_{ab} in one switching period T_s. It can be found that the time average of U_{ab} is V_{out}, which infers that the magnitude of V_{out} is controlled by varying duty cycle D. Furthermore, the variation range of D is defined as {-1 to 1}. D is negative when V_{in} and V_{out} have the opposite polarity. As shown in Fig.2, the circuit operates in Mode I and IV when D is positive. It enters the operation mode II and III when D changes to negative. The overall way of selecting the switching patterns according to different operational modes and stages are given in Table I. As it infers in the operational strategy, the input ac voltage is modulated into high frequency AC voltage Unp1 by the chopping of the input cycloconverter. The output cycloconverter acts like a rectifier which is demodulated the AC voltage into uni-polarity pulse wave Uab. The output voltage Vout is then filtered out by the output LC filter. An isolated AC output voltage can thus be generated without implementation of line frequency transformer. The steady state analysis of the circuit is simple as it is essentially attributed to buck-type.

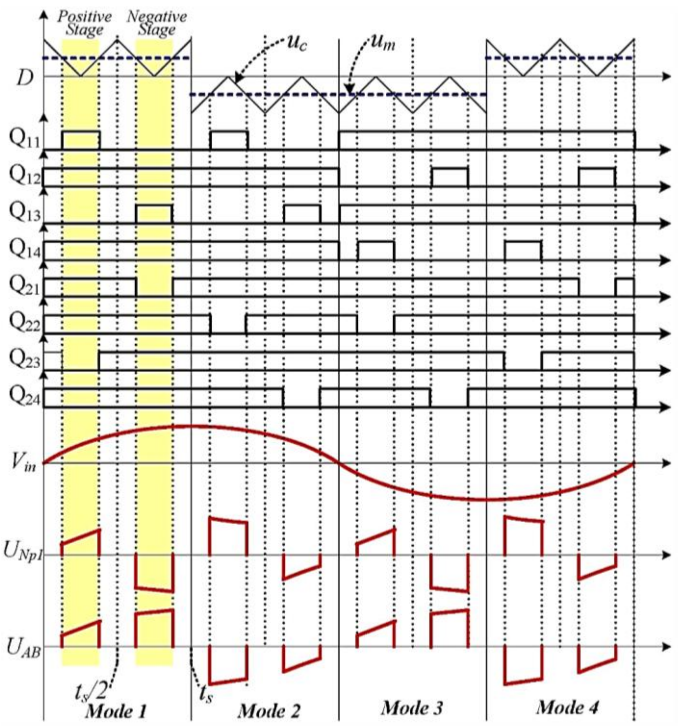


Fig.2 Demonstration of gate signals and crucial waveforms

By applying the principle of inductor volt-second balance and using the small-ripple approximation, the relationship of V_{in} and V_{out} can be given by:

$$V_{out} = V_{in}.D.N \quad (1)$$

Based on (1), V_{out} can be easily controlled by varying duty cycle D. The output range of V_{out} is {- V_{in}N to V_{in}N }, which shows its bi-directional control ability when applied to voltage compensation system.

3 FUZZY LOGIC CONTROLLER FOR AHFL AC-AC CONVERTER

The fuzzy control system consists of five parts: fuzzy controller, interface of input and output, control object, execute institution and sensors [13], which actually translates the knowledge and experience of expert into the control law. Because FC is not designed based on the mathematical analysis of a process model, MATLAB/ SIMULINK and Fuzzy Logic Toolbox are used for simulation analysis. The actual instantaneous output voltage is sensed, sampled and compared with sinusoidal reference value to create the error voltage. Discrete error voltage *E(k)* and its change of error *Ec(k)* are processed by the FC through fuzzification, fuzzy inference and defuzzification operations. The change of control signal $\Delta u(k)$ as the output variable of primary FC is added to the control signal, *U(k)* to give a updated value of switching angles to compensate properly with any loading variation. In the FC system, weight factor *Ke*, *Kc* and scaling factor *Ku* are very important to the static and dynamic performance. The effect of the gain settings for a conventional PI controller in a closed loop system is related to the scaling factors adjustment in the FC, which can be approximated as a actual PI controller. Referring to the conventional integral digital PI controller.

$$\Delta u(k) = K_P \Delta e(k) + K_I e(k) \quad (2)$$

Referring to FC presented in [14].

$$K_U \Delta u(k) = K_C Ec(k) + K_E E(k) \quad (3)$$

Relating (2) and (3),

$$K_P \equiv \frac{K_C}{K_U} \text{ and } K_I \equiv \frac{K_E}{K_U} \quad (4)$$

Referring to conventional PI control experience [15], the following conclusions can be gained:

- A higher value of Ke will cause a long transition progress or even an overshoot. On the contrary, a smaller Ke will result in a poor dynamic response and a large system error.
- Increscent Kc can make the controller sensitive, which will avoid overshoot of the system output and bring out a slow dynamics. Otherwise, a large overshoot or even a surge will occur.
- The value of Ku will influence directly the output scale of controller. By reducing Ku, a steady output can be achieved. On the other hand, a large Ku makes for a proper dynamics.A compromise should be carried when selecting an appropriate Ku.

In Fig.3, a fuzzy controller based on scaling factor self-adjusting online is designed. The assistant fuzzy controller is introduced to modify the scaling factor of primary fuzzy controller for better robust depending on various load features. The basic rules of assistant fuzzy controller are shown as follows. Scaling factor *Ku* should be reduced for a small output overshoot and short rise-time when error *E* is large and has the inverse sign with the change of error, *EC*. On the contrary, *Ku* should be increased when *E* and *EC* has the same sign, because system output is drawing away with reference at this point. On the other hand, when *E* has a large value, scaling factor *Ku* should have a large change range. It should be reduced if system output draws away from reference after drawing on it. This method is in fact a gain-variable nonlinear controller which is unattached with model [16]. Rules of primary FC and assistant FC are shown in Table II and Table III respectively.

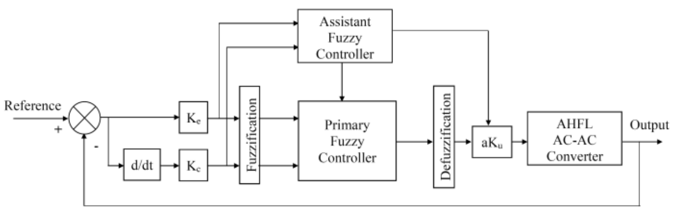


Fig.3 Block diagram of Fuzzy controller

The controller is designed as a double closed-loop of Output voltage instantaneous FC and inductor current P Control, which is shown in Fig.2. As the input variations of PI-type primary fuzzy controller and PD-type assistant fuzzy controller, *E* and *EC* have the definition of error and the change of error respectively [8].

TABLE II. PRIMARY FC RULES

EC/E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

TABLE III ASSISTANT FC RULES

EC/E	NB	NM	NS	ZE	PS	PM	PB
NB	VB	VB	VB	B	M	SM	VS
NM	VB	VB	B	B	BM	SM	S
NS	VB	BM	NM	B	VB	S	S
ZE	SM	M	BM	VS	M	BM	SM
PS	S	SM	S	VB	B	BM	VB
PM	S	SM	BM	B	B	VB	VB
PB	VS	SM	M	B	VB	VB	VB

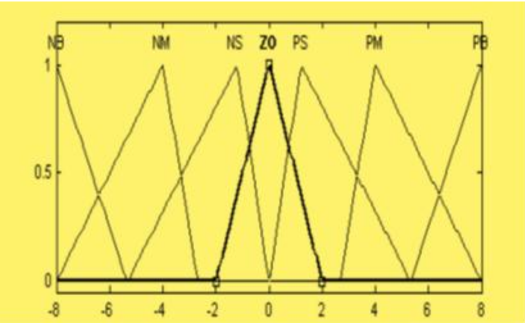
They are all divided into seven fuzzy subsets from [-8, +8]: {NB, NM, NS, Z, PS, PM, PB}. As shown in Fig.3, their membership functions have the same geometry of asymmetric Triangle [9]. Δu as the output variation of primary fuzzy controller is also divided into seven subsets, which is not like α , the output of assistant fuzzy controller. α is divided into seven fuzzy subsets from [0,1], {VS, S, SM, M, BM, B, VB}. But they have the same membership functions of symmetrical triangle. The inference logic of MAX-MIN method is employed in two fuzzy controllers, similarly the defuzzification method of centroid formula is shown in (4) [9].

$$u = \frac{\sum_{i=1}^{n} \mu(u_i) \times u_i}{\sum_{i=1}^{n} \mu(u_i)} \quad (5)$$

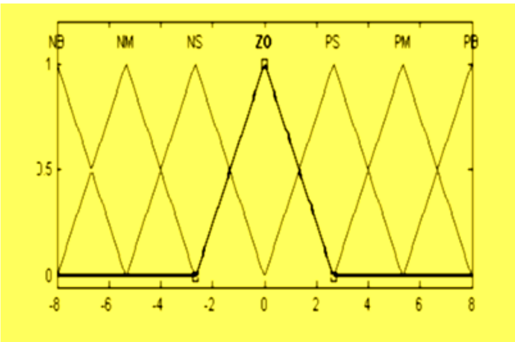
4 Sinusoidal Pulse Width Modulation Technology

Traditionally, the single-phase AC-AC converter is considered as cannot output the voltage with arbitrary frequency and phase. In order to break the limitation, DVQS voltage synthesis concept is proposed in [7]. Based on this concept, the Even Harmonics Modulation (EHM) scheme is also proposed in [7] to generate the required compensating sine wave output [7 -10]. However, the EHM scheme still has its own limitation such that the frequency of the output voltage can only be the integral multiple of the line frequency. Furthermore, only the balanced grid faults are concerned in all the scenarios in [17-19]. In this paper, Sinusoidal Pulse Width Modulation (SPWM) technology is proposed to replace the EHM scheme and improve the performance of AHFL converter when dealing with the unbalanced harmonics and grid fault by generating the unbalanced compensating voltage output. The basic concept of SPWM can be described as follows. At first, the three-phase input grid voltage V_m is assumed as the balanced pure sine in positive sequence, which is given by:

$$\begin{aligned} V_{ina} &= V_m \sin \omega t \\ V_{inb} &= V_m \sin(\omega t - 120^o) \\ V_{inc} &= V_m \sin(\omega t + 120^o) \end{aligned} \qquad (6)$$



(a) Membership functions of *E* and *EC*



(b) Membership function of Δu

Fig 4. Shape of membership functions for SAFC

Where V_m is the amplitude of V_{in} and the angular frequency ω can be 2πf . As indicated in DVQS concept [10], the duty ratio D of the AC-AC converter is no need to fix but can add a specified modulation wave which may vary with time. The products of the injection can not only be the fundamental frequency output but also the harmonics output. Therefore, the voltage synthesis process of SWM has three steps. Firstly, the desired voltage output is separated into several decoupled components with different frequency and sequence, including the fundamental components, harmonics components and even the components with the fractional multiple of the line frequency. Following this, several specified modulation waves are implemented to the AC-AC converter to generate each required component output. At last, the outputs are added together to reform the desired voltage output. The following parts are to figure out how to decide the specified modulation waves used for voltage synthesis. Generally, the desired voltage is separated into the fundamental voltage, the voltage in positive sequence and the voltage in negative sequence.

4.1 Generation of fundamental voltage

The SWM scheme for generating the fundamental voltage is to add the fixed DC component to the modulation wave of D which is expressed as:

$$\begin{aligned} D_{a0} &= K_{0a} \\ D_{b0} &= K_{0b} \\ D_{c0} &= K_{0c} \end{aligned} \qquad (7)$$

Substitute (6) and (7) to (1), the output voltage of the converter in each phase is

$$\begin{aligned} V_{outa0} &= V_{ina}.D_{a0}.N = K_{0a} V_m \sin \omega t \\ V_{outb0} &= V_{inb}.D_{b0}.N = K_{0b} V_m \sin(\omega t - 120^o) \\ V_{outc0} &= V_{inc}.D_{c0}.N = K_{0c} V_m \sin(\omega t + 120^o) \end{aligned} \qquad (8)$$

It can be concluded in (8) that the output voltage is in phase with the input voltage as well as the frequency is the same. The amplitudes are different if $K_{oa} \neq K_{ob} \neq K_{oc}$. It is used as voltage variation compensation by controlling the value K_o, which is the common control strategy for the AC-AC converters applying in voltage compensation [5-9].

4.2 Generation of voltage in positive sequence

The SWM scheme for generating the positive sequence voltage for compensation is to add a series of negative sequence sinusoidal waves to the modulation wave of D. The amplitude of the sinusoidal waves is expressed as K_i and the corresponding angular frequency and phase are ω, and ϕ_i respectively. The modulation wave of D for converters in each three-phase is the summation of all the sinusoidal components, which is given by:

$$\begin{aligned} D_{ap} &= \sum K_i \sin(\omega_i t - \varphi_i) \\ D_{bp} &= \sum K_i \sin(\omega_i t + 120^o - \varphi_i) \quad \{\omega_i > \omega_i \\ D_{cp} &= \sum K_i \sin(\omega_i t - 120^o - \varphi_i) \end{aligned} \qquad (9)$$

Substitute (6) and (9) to (1), the output voltage of the converter in each phase is:

$$\begin{aligned} V_{out\_ap} &= V_{ina}.D_{ap}.N \\ &= \sum V_m K_i \left\{ \frac{1}{2}\cos\left[(\omega_i - \omega)t - \varphi_i\right] - \frac{1}{2}\cos\left[(\omega + \omega_i)t - \varphi_i\right] \right\} \\ V_{out\_bp} &= V_{inb}.D_{bp}.N \\ &= \sum V_m K_i \left\{ \frac{1}{2}\cos\left[(\omega_i - \omega)t - 120^o - \varphi_i\right] - \frac{1}{2}\cos\left[(\omega + \omega_i)t - \varphi_i\right] \right\} \\ V_{out\_cp} &= V_{inc}.D_{cp}.N \\ &= \sum V_m K_i \left\{ \frac{1}{2}\cos\left[(\omega_i - \omega)t + 120^o - \varphi_i\right] - \frac{1}{2}\cos\left[(\omega + \omega_i)t - \varphi_i\right] \right\} \end{aligned} \qquad (10)$$

It can be found that the output voltage consists of two quadrature components. The first harmonic component in positive sequence has the angular frequency equal to ω_i - ω and the phase equal to $-\phi_i$. The amplitude, phase and frequency of this component are all controllable by setting proper ω_i , K_i and ϕ_i . In order to keep this component in positive sequence, the condition $\omega_i - \omega > 0$ should be satisfied. The second harmonic components are in zero sequence, which means that it cannot propagate in the three-phase system. As a result, after the implementation of the negative sequence sinusoidal waves to the modulation wave of D a series of new controllable voltage outputs in positive sequence can be synthesised in the output voltage. Also, the by-products can be eliminated without adding additional filters.

4.3 Generation of voltage in negative sequence

Different from the positive sequence voltage generation, under this condition, negative sequence sinusoidal waves with ω_j

$-\ \omega < 0$ are implemented to the modulation wave of D . The expression for D is given by,

$$D_{an} = \sum K_j \sin(\omega_j t - \varphi_j)$$
$$D_{bn} = \sum K_j \sin(\omega_j t + 120^o - \varphi_j) \quad \{\omega_j < \omega \tag{11}$$
$$D_{cn} = \sum K_j \sin(\omega_j t - 120^o - \varphi_j)$$

If $\omega_j < 0$, (10) is changed to

$$D_{an} = -\sum K_j \sin(-\omega_j t + \varphi_j)$$
$$D_{bn} = -\sum K_j \sin(-\omega_j t - 120^o + \varphi_j) \tag{12}$$
$$D_{cn} = -\sum K_j \sin(-\omega_j t + 120^o + \varphi_j)$$

which represent a positive sequence sinusoidal wave. Despite of the zero sequence components, negative sequence components are included in the output voltage by modulation, which has the angular frequency equal to ω - ω_j , the phase equal to φ_i and the amplitude is $V_m K_j$ as well.

4.4 Combination of output voltage

The final output is given in (13). It is simply to add all the modulation waves together to be the modulation wave D for the AC-AC converter. The zero components are excluded in the final results of the output voltage. It is inferred in (13) that by applying the SWM technology, arbitrary voltage output is realized using the single-phase based AC-AC converter. Particularly, the frequency range of outputs are $(0,\infty)$, which means that the output voltage is not limited to the integral multiple of the line frequency. As a result, compared to EHM, the proposed strategy is more flexible which can handle all the harmonics voltage generation including unbalanced voltage and can be potentially used in AC applications such as motor drive etc.

5 Configuration Of Voltage Compensation System

One of the typical applications for the proposed AHFL converter with SWM scheme is the voltage compensation system. Fig.5 shows the system configurations for voltage compensation.

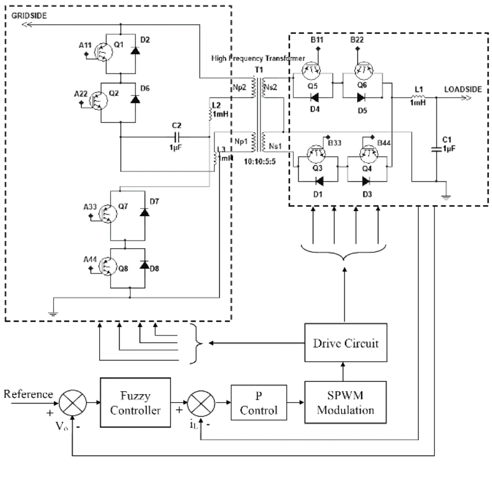


Fig.5 Typical system configuration with proposed IHFL AC-AC converter for voltage compensation

$$V_{out\_an} = V_{ina}\cdot(D_{a0} + D_{ap} + D_{an}).N = K_{0a}V_m \sin(\omega t) + \sum\left\{\frac{1}{2}V_m K_i \cos[(\omega_i - \omega)t - \varphi_i] + \frac{1}{2}V_m K_j \cos[(\omega - \omega_j)t + \varphi_j]\right\}$$
$$V_{out\_bn} = V_{inb}\cdot(D_{b0} + D_{bp} + D_{bn}).N = K_{0b}V_m \sin(\omega t - 120^o) + \sum\left\{\frac{1}{2}V_m K_i \cos[(\omega_i - \omega)t - 120^o - \varphi_i] + \frac{1}{2}V_m K_j \cos[(\omega - \omega_j)t + 120^o + \varphi_j]\right\}$$
$$V_{out\_cn} = V_{inc}\cdot(D_{c0} + D_{cp} + D_{cn}).N = K_{0c}V_m \sin(\omega t + 120^o) + \sum\left\{\frac{1}{2}V_m K_i \cos[(\omega_i - \omega)t + 120^o - \varphi_i] + \frac{1}{2}V_m K_j \cos[(\omega - \omega_j)t - 120^o + \varphi_j]\right\}$$

The voltage at the PCC is distorted by the nonlinear load such as diode-rectifier with resistance-capacitance load. The nonlinear load can be connected to either the three-phase or single-phase. Thus the voltage harmonics at PCC could be unbalanced. At the same time, one three-phase critical load requires pure sine voltage input. Three individual AHFL converters are applied to each phase to realize voltage compensation function. The converter is placed between the grid and the critical load, which can be considered as a controllable voltage source to inject a controllable compensation voltage in series with the grid voltage to compensate for the harmonics and voltage variations. The input power of the AHFL converter is drawn from the grid side. The input inductor L_i is added to minimize the switching harmonics superposed to the grid. The relationship between the system input voltage V_{sys_in} and output voltage V_{sys_out} is given by:

$$V_{sys\_out} = \begin{pmatrix} V_{sys\_outa} \\ V_{sys\_outb} \\ V_{sys\_outc} \end{pmatrix} = \begin{pmatrix} V_{sys\_ina} \\ V_{sys\_inb} \\ V_{sys\_inc} \end{pmatrix} - \begin{pmatrix} V_{outa} \\ V_{outb} \\ V_{outc} \end{pmatrix} = \begin{pmatrix} V_{sys\_ina} \\ V_{sys\_inb} \\ V_{sys\_inc} \end{pmatrix} \cdot \left(1 - \begin{pmatrix} D_a \\ D_b \\ D_c \end{pmatrix} N\right) \tag{14}$$

Where V_{sys_in} is also the input voltage of the AHFL converter and the compensating voltage V_{out} is the output voltage of the AHFL converter.

6 Simulation Result

Simulation studies are carried out in MATLAB/Simulink to validate the proposed AHFL converter as well as the SPWM scheme. The specification of the system are given by: V_{sys_in} : 220 V; V_{sys_out}: 220V; V_{line}: 380V; P_{out}: 3kW; f_s: 10kHz; C_i: 3 μF; C_o: 5 μF; C_{s1} : 1 μF; L_i: 2mH; L_o: 0.68mH . Three 1 mH inductors L_s are connected in series with the output of three sine voltage sources in order to simulate a weak grid. The Simulink diagram is shown in fig.6. The dynamic performances of the Conventional and Proposed methods are shown in fig.7 & fig.8 respectively.

7 Conclusions

In this paper, The AHFL AC-AC converter for voltage compensation is proposed. The AHFL converter has the

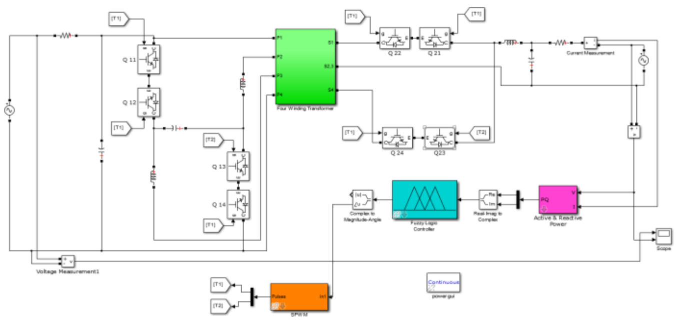
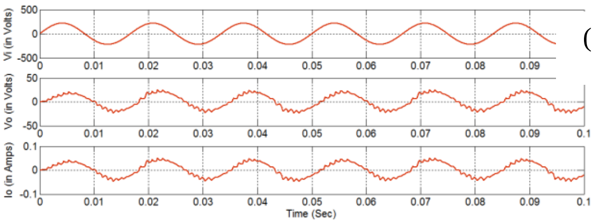


Fig. 6 Simulink Diagram of Proposed AHFL AC-AC Converter Scheme



(13)

Fig.7. Simulation results of input and output line voltage and current for conventional method

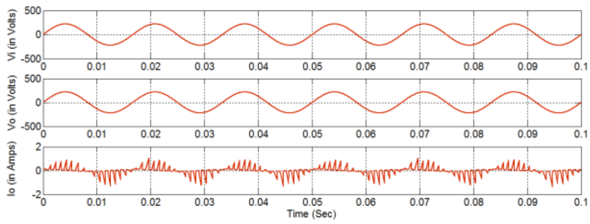


Fig.8. Simulation results of input and output line voltage and current for proposed method

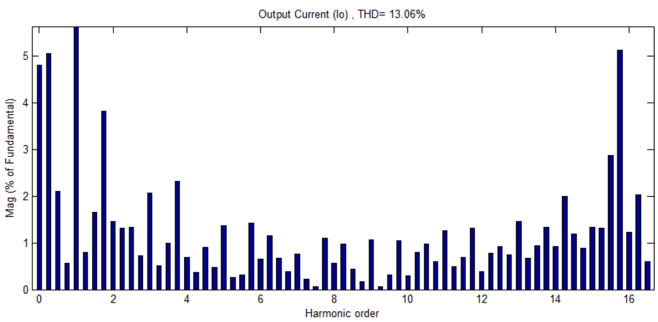


Fig.9. Simulation results of harmonic spectra of output line current for Proposed method

advantages such as no large electrolytic capacitors and no line frequency transformer. So that the cost of the system is reduced and the reliability is improved. The new proposed SPWM technology can be used to achieve the function of unbalanced voltage harmonics elimination to increase the performance of the voltage compensation. The Fuzzy logic Controller proposed in this paper has a simple design progress no need of exact mathematics model of AC-AC Converter and can operate automatically without man-made effect. It provides insensitivity to plant-parameter variations and external distribution such as making for overcoming perturbations caused by Non-linear loads. The simulation results are show the effectiveness of the proposed AHFL converter and SWM technology.

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