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Direct AC-AC High Frequency Link Converter Using Sinusoidal PWM Technique

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ABSTRACT: A direct AC-AC converter based on high frequency link concept is proposed to reduce the harmonics present in the output current when connected to the non linear loads in the distribution system. The proposed system converts one unregulated sinusoidal voltage with high THD into another regulated sinusoidal voltage with low THD using sinusoidal pulse width modulation without any DC link storage element such as large electrolyte capacitor. Therefore the proposed system has reduced size, weight and cost. Thus the system reliability can be enhanced. The proposed converter provides bidirectional power flow. The sinusoidal pulse width modulation employed in proposed system act as series active power filter. Direct AC-AC high frequency link converter is simulated by MATLAB/simulink. The simulation result shows the effectiveness of the proposed three phase direct AC-AC converter.

Keywords: Direct AC-AC high frequency link converter, harmonics elimination, voltage regulation.

INTRODUCTION

Harmonics present in the three phase distribution system leads to significant problems such as overloading of neutrals[1]. overheating of transformer, nuisance tripping of circuit breakers, skin effect, voltage distortion, over stressing of power factor correction capacitors, zero crossing noise, eddy current loss in induction motor etc.. A large number of power electronics converters are used in power line condition applications[2]. Traditionally inverter type converters are mainly used by the industries as well as researchers because of its good dynamic response, harmonics performance, voltage utilization and so on[3] It has the drawback of low reliability because of the requirement of large dc link storage element such as large electrolytic capacitors to provide stiff DC voltage[8]-[10]. It has short life time, poor performance at high temperatures and susceptible to hazardous failures [4]. The use of large dc link capacitor increases the system size, weight and cost. The converter becomes heavy and bulky [5]. To reduce the size of the dc link storage element, several investigation are undergone, researchers continue to investigate solutions. In order to overcome the drawbacks distributed power flow controller is proposed which has the same function of inverter type converter eliminates dc link between the series and shunt inverters [6]. It has high reliability and lower cost than traditional converters. But distributed power flow controller still has large capacitors, therefore reliability issue essentially not been solved. The large storage element can be eliminated by adopting the direct AC-AC conversion technology, such as the ac-ac chopper or the matrix converters. Matrix converters do not require large energy storage dc link capacitors [7]-[10]. It has application in various fields. But matrix converter solutions have complex circuit structures and complex control algorithms. During fault condition it is difficult to control because the three phase ac inputs are directly coupled to the three AC outputs.

An improved solution to this problem is high frequency AC link converters. Here, the traditional DC-link is replaced by resonant AC link formed by parallel connected capacitor and inductor [11]. A high frequency link allows the flexibility of varying the link voltage to meet the needs of the source and load side. High frequency link provides isolation between source and load. In order to overcome the drawback of back to back converter, High frequency AC-link one- step bidirectional power converter is proposed [12]. The pulse density modulation is used to control the currents. It consist of a six switch input converter and a six switch output converter. Input phase charge the link and it discharge into the output because of the links unidirectional nature, due to the resonant “fly back” there is a large dead time which reduces the power capability by about 30%. At low power factor or low voltage it is also limited in operation response due to its inability to supply current. Among these solutions either too many switches or full rated components are necessary which increases the cost. Control are always complex which leads to difficult

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fault ride through handling [13], [14].A new concept in the direct ac-ac power conversion based on single phase based AC-AC topology proposed [15]. It has a much simpler structure. But it mainly focuses on the fundamental voltage quality issue only such as voltage sag or variation in reactive power. Due to natural limitations of single phase circuit harmonics problems are ignored [16].

Recently a new direct AC-AC power conversion concept has been proposed [17],[18],. Dual virtual quadrature source voltage synthesis theory is applied to traditional AC-AC choppers to control the power flow or eliminate voltage harmonics from the grid. But it requires a large number of passive components and a line frequency transformer. The former control theory is problematic when dealing with an imbalanced grid fault.

In this paper, a new improved single phase based direct AC-AC high frequency link converter is proposed to reduce the harmonic present in three phase distribution system. The concept of reference frame theory based sinusoidal pulse width modulation approach is utilized in proposed converter. The operational principle of a proposed push–pull forward direct AC-AC high frequency link converter is explained.High reliability solution are achieved using the proposed converter which replaces traditional inverter-type converters in power transmission and distribution system. In this paper, Single-phase direct ac–ac converter applicable to the new SPWM approach is derived.

II. DIRECT AC-AC HIGH FREQUENCY LINK CONVERTER

High-frequency high-density power conversion is realized along with galvanic isolation from a high-frequency transformer which is the objective of direct AC-AC high frequency link (DAHFL) power converter. Furthermore, low frequency voltage output can be generated without magnetic saturation. The proposed converter has a high frequency link transformer to provide contactless power transfer and galvanic isolation between source side and load side. The converter has eight bidirectional switches to provide bidirectional power flow. The system reliability can be enhanced since there is no large electrolytic capacitor is required. Furthermore, the cost, weight, and size are reduced.

A. Circuit description

The proposed push–pull forward direct AC-AC high frequency link converter is divided into two parts, namely the input push–pull forward converter and the output push–pull converter. Divided parts are connected through galvanic isolation high frequency link transformer which is shown in Figure 1.

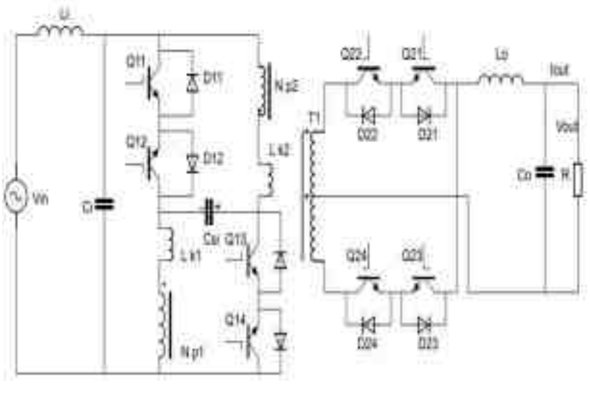

Figure 1.Circuit diagram of direct AC-AC high frequency link converter

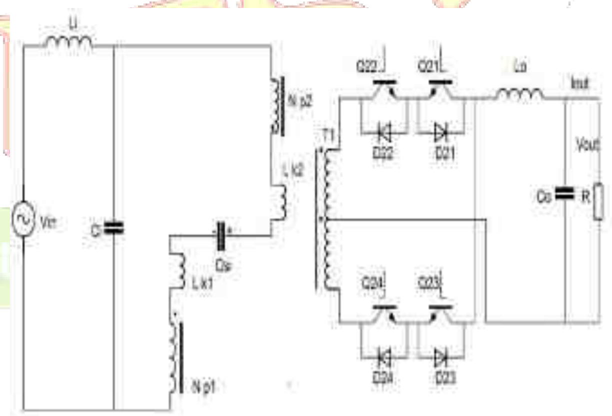

Figure 2. Equivalent circuit for zero stage

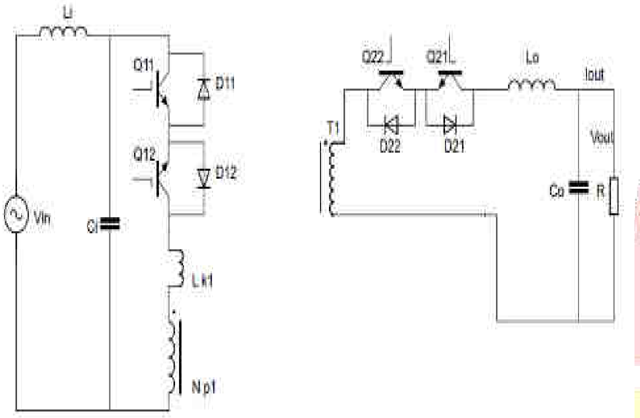

Figure 3.Equivalent circuit for positive stage

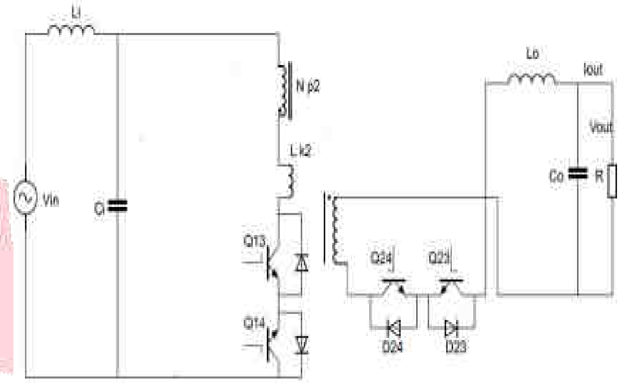

Figure 4.Equivalent circuit for negative stage

Np1, Np2, Ns1, and Ns2 are the turns for each winding of the high-frequency transformer T1. Where Np1 = Np2 and Ns1 = Ns2. The turn ratio N equals Ns1 /Np1.

B. Modes of operation

Depending on polarity of the input voltage V_{in} and output voltage V_{out} the direct AC-AC high frequency link converter has four operational modes. By varying duty cycle D the magnitude of Vout is controlled. Duty cycle can be varied from -1 to 1. D is negative when input and output voltages have the opposite polarity. When D becomes negative converter operates in Modes 2 and 3. When D is positive converter operates in Modes 1 and 4. In each operating mode, one switching period is divided into three stages, namely

- Positive stage
- Negative stage
- Zero stages

C. Mode 1

The equivalent circuits of Mode 1 of the circuit are shown in Figures 2–4. In this mode, the polarities of V_{in} and V_{out} are both positive. During the operation Q12, Q14, Q22, and Q24 are normally ON to reduce the switching loss.

a. Zero Stage

The equivalent circuit for zero stage is shown in Figure 2. During the zero stage, Q21 and Q23 are switched ON; Q11 and Q13 are switched OFF. The current in Lo freewheels only in both secondary windings of the output side and the transistors. The polarity of voltage across the primary side of T1 remains unchanged.

b. Positive Stage

The equivalent circuit for positive stage is shown in Figure 3. The time period for positive stage is 1/2DTs. During the positive stage operation, Q11 and Q21 are switched ON; Q13 and Q23 are switched OFF. As a result, the voltage across the primary side of high frequency link transformer T1 is positive, which denotes the positive excitation process. During the state Vout is positive Since Q21 is ON.

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c. Negative Stage

The time period of negative stage is 1/2DTs. In each switching period Ts the duration of negative stage is kept the same with the positive stage to ensure the magnetic reset of the high-frequency transformer. The equivalent circuit for negative stage is shown in Figure 4. During the negative stage, Q13, Q23 are turned ON and Q11, Q21 are OFF. Vout is still positive. As a result, the voltage across the primary side of high frequency link transformer experiences the negative excitation process.

TABLE I.

SELECTION OF SWITCHING PATTERNS ACCORDING TO DIFFERENT MODES AND STAGES

MODE			Q11	Q12	Q13	Q14	Q21	Q22	Q23	Q24
I	$V_{in} > 0$	Positive	1	1	0	1	1	1	0	1
	$V_{out} > 0$	Negative	0	1	1	1	0	1	1	1
		Zero	0	1	0	1	1	1	1	1
II	$V_{in} > 0$	Positive	1	1	0	1	1	0	1	1
	$V_{out} < 0$	Negative	0	1	1	1	1	1	1	0
		Zero	0	1	0	1	1	1	1	1
III	$V_{in} > 0$	Positive	1	0	1	1	1	1	0	1
	$V_{out} > 0$	Negative	1	1	1	0	0	1	1	1
		Zero	1	0	1	0	1	1	1	1
IV	$V_{in} > 0$	Positive	1	0	1	1	1	0	1	1
	$V_{out} > 0$	Negative	1	1	1	0	1	1	1	0
		Zero	1	0	1	0	1	1	1	1

According to different operational modes and stages the method of selecting the switching patterns are given in Table 1. The energy in the leakage inductors Lk1 and Lk2 of T1 can be recycled by adding one clamping capacitor Cs1.

III. BASIC PRINCIPLE OF SINUSOIDAL PULSE WIDTH MODULATION

Initially, a three-phase utility input voltage V_{in} is assumed as a balanced pure sine positive sequence, which is expressed by

$$V_{ina} = V_m sin\omega_1 t$$

$$V_{inb} = V_m \sin(\omega_1 t - 120°)$$

$$V_{inc} = V_m \sin(\omega_1 t + 120°)$$

(1)

Where V_m is the amplitude of V_{in} and the angular frequency ω_1 can be 2π × supply frequency rad/s.

The set dc component is added to the modulation wave of D for the generation of fundamental voltage, which is expressed as

$$D_{ao} = K_{oa}$$

$$D_{bo} = K_{ob}$$

$$D_{co} = K_{oc}$$

(2)

The basic relationship between the input and the output voltage is given by

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$$V_{out} = V_{in} \cdot D. \quad (3)$$

Substituting equation (1) and equation (2) into equation (3), the output voltage of the converter in each phase is

$$V_{outa0} = V_{ina} \cdot D_{a0} = K_{0a} V_m \sin \omega_1 t$$

$$V_{outb0} = V_{inb} \cdot D_{b0} = K_{0b} V_m \sin(\omega_1 t - 120°)$$

$$V_{outc0} = V_{inc} \cdot D_{c0} = K_{0c} V_m \sin(\omega_1 t\, 120°) \quad (4)$$

From equation (4) it can be inferred that the output voltage and the input voltage are in phase at same frequency. The amplitudes are dissimilar if $K_{0a} \neq K_{0b} \neq K_{0c}$. By adjusting the value K_0, a fundamental voltage with arbitrary amplitude can be synthesized.

$$V_{out_a} = V_{ina} \cdot \left(D_{a0} + D_{ap} + D_{an}\right) = K_{0a} V_m \sin(\omega_1 t) + \sum \begin{matrix} \{\frac{1}{2} V_m K_i \cos[(\omega_i - \omega_1)t - \varphi_i] \\ + \frac{1}{2} V_m K_j \cos[(\omega_1 - \omega_j)t + \varphi_j]\} \end{matrix}$$

$$V_{out_b} = V_{inb} \cdot \left(D_{b0} + D_{bp} + D_{bn}\right)$$

$$= K_{0b} V_m \sin(\omega_1 t - 120°) + \sum \begin{matrix} \{\frac{1}{2} V_m K_i \cos[(\omega_i - \omega_1)t - 120° - \varphi_i] \\ + \frac{1}{2} V_m K_j \cos[(\omega_1 - \omega_j)t + 120° + \varphi_j]\} \end{matrix}$$

$$V_{out_c} = V_{inc} \cdot \left(D_{c0} + D_{cp} + D_{cn}\right) =$$

$$K_{0b} V_m \sin(\omega_1 t + 120°) + \sum \begin{matrix} \{\frac{1}{2} V_m K_i \cos[(\omega_i - \omega_1)t + 120° - \varphi_i] \\ + \frac{1}{2} V_m K_j \cos[(\omega_1 - \omega_j)t - 120° + \varphi_j]\} \end{matrix} \quad (5)$$

The final output is given by equation (5). The accumulation of the entire modulation waves is the final modulation wave for the AC–AC converter. By varying the frequency of the sine waves in the modulation wave the output frequency is controlled and it is not restricted to integral multiples of the line frequency. When compared to Even Harmonic Modulation, the proposed scheme handles all the harmonic current synthesized in the three phase distribution system including unbalanced voltages. It is more flexible.

The output voltages can be generated by injecting a series of sine waves with different frequencies to the modulation waves. The proposed scheme used in other AC applications such as motor drives, etc. The input voltage is assumed as the balanced pure sinusoidal positive sequence but it is not true during the fault condition. The utility voltage is non-ideal or unbalanced due to the fault current. At this time, the input includes zero sequence fundamental voltages, negative sequence, and harmonic voltages in addition with positive sequence. Therefore

The non-ideal or unbalanced input voltage can be expressed as

$$V_{ina} = V_m \sin \omega_1 t + \dot{v}'_{a1} + \dot{v}_{ah}$$

$$V_{inb} = V_m \sin(\omega_1 t - 120°) + \dot{v}'_{b1} + \dot{v}_{bh}$$

$$V_{inc} = V_m \sin(\omega_1 t + 120° + \dot{v}'_{c1} + \dot{v}_{ch} \quad (6)$$

Where v_h represents the harmonic voltages.

v'_1 represents the negative sequence or zero sequence fundamental voltages,

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According to the equation (3), following the modulation, unwanted byproducts in the outputs is generated by multiplying v'_1 and v_h with duty cycle D. Following the similar analysis given previously, these byproducts can also be decomposed into several components with a unique frequency and sequence. The amplitudes of the v'_1 and v_h are not important. Since each phase is controlled by individual converter during fault condition such as one phase is short circuited or drops its voltage. Remaining phases are unaffected, the closed loop control saturates. Only faulted phase required attention whether to disconnect or continue if it is restorable transient. Each phase is connected to separate converter therefore the protection strategy is easier than matrix converter because in matrix converter single converter couples and controls all three phases. By varying the switching patterns the circuit achieves the bipolarity output capacity which means that the output voltage can be out phase and in phase with the input. The circuit uses a high frequency transformer. In every switching period magnetizing current reset occurs. As a result circuit delivers isolated low frequency AC voltage. By the chopping of the primary side converter the input AC voltage is modulated into high frequency AC voltage. High frequency transformer isolate primary and secondary side converter. Secondary side converter converts high frequency AC voltage into unipolarity pulse wave. The output side LC filter filters the output voltage and generates isolated AC voltage at fundamental frequency without line frequency transformer.The proposed direct AC-AC high frequency link converter circuit is buck type therefore the steady state analysis is simple.

The relationship between V_{in} and Vout is

Vout=V_{in}·D·N.
(7)

Based on equation (7), output voltage can be controlled by varying the duty cycle of modulation signal. The output range of Vout is [$-V_{in}$ N, V_{in} N].

IV. SYSTEM CONFIGURATION

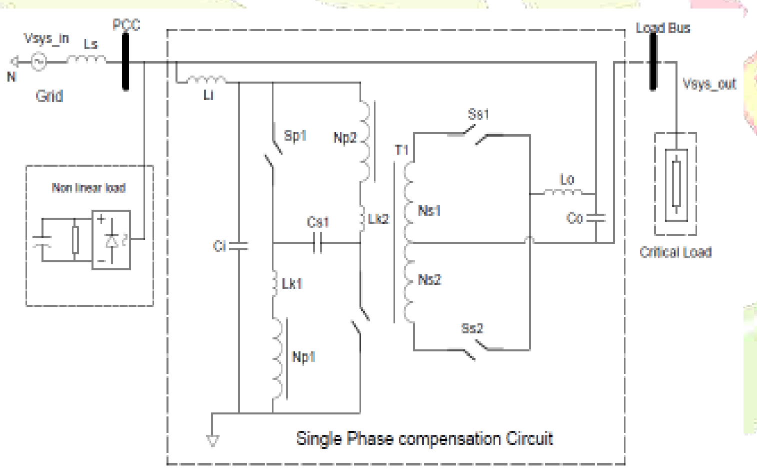

Figure 5. Typical system configurations with proposed converter for harmonics filtering

The system configurations are shown in Figure 5. The voltage at the Point of Common Coupling (PCC) is distorted by a nonlinear load such as diode rectifier with a resistive-capacitive load. The nonlinear load can be connected to either a three phase or a single phase. Thus, the voltage harmonics at the PCC could be unbalanced. Also the fundamental voltage is different from the rated voltage of the system that needs to be compensated. Also one three-phase critical load requires pure sine rated voltage input. Three individual direct AC-AC high frequency link converters are installed on each phase to realize a voltage compensation function. The converter is placed between the grid and the critical load, which can be considered a controllable voltage source to inject a controllable compensation voltage in series with the grid voltage to compensate for the harmonics and voltage variations.

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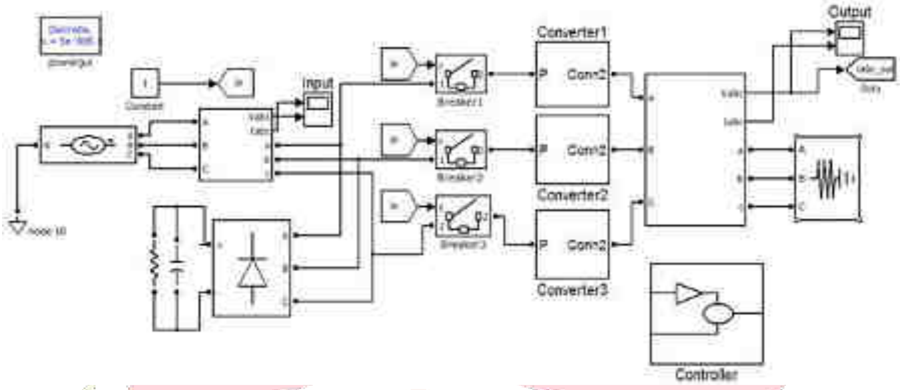

Figure 6. Simulation circuit of three phase direct AC-AC high frequency link converter.

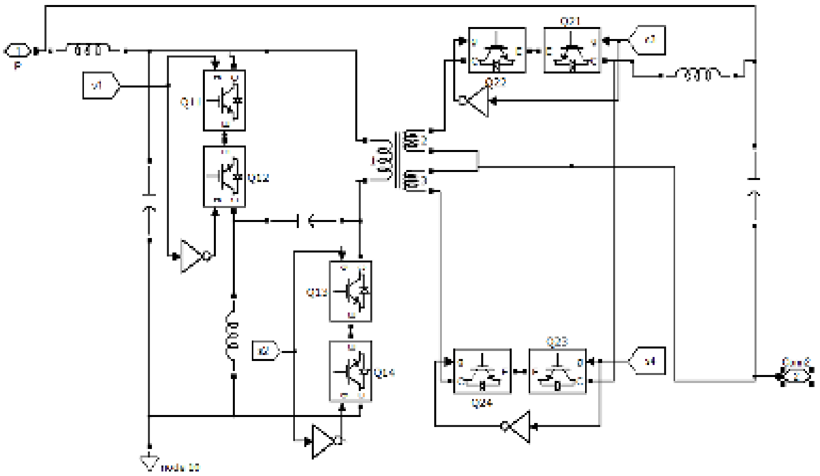

Figure 7. Single phase structure of direct AC-AC high frequency link converter.

The simulation of direct AC-AC high frequency link converters for three phase AC power system to eliminate the harmonics produced by the non linear loads has been done using MATLAB/SIMULINK. Each phase is connected with individual converter in series. The IGBT switches are used as a switching device because of high switching speed and low switching time. System is designed to eliminate the third, fifth, seventh and ninth harmonics caused by the nonlinear load connected to three phase supply. The spectrum of the output voltage is taken to determine the THD of the three phase system. The main advantage of the direct AC-AC high frequency link converter over the conventional converter is the elimination of bulk energy storage element; reduce the size of filter required; Provides isolation between output and input and two stage direct AC-AC conversion. Simulation diagram of direct AC-AC High frequency link converter connected in series with three phase AC supply is shown in Figure 6.

V. CLOSED-LOOP CONTROL STRATEGY

The control strategy of the Direct AC-AC high frequency link converter is to synthesize the required fundamental voltage and the harmonics voltage out phase with the system harmonics that have the same amplitude and phase. The overall control block is shown in Figure 9. The three-phase system output voltage is sampled as the closed-loop control input. The control block consists of several decoupled control loop including harmonic control loops and the fundamental voltage loops. The fundamental voltage variations are compensated by using the fundamental voltage loop. In the controller part of the architecture, the three-phase voltage after the compensation V_{OUT} is sampled first. In order to

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extract the amplitude of each nth harmonics or fundamental component in V_{OUT}, Park's transformation is introduced to transform the output "abc" voltage to the "dq" voltage in each frequency order. This method assumed that the voltage is almost balance. After the extraction, digital low-pass filters are employed to eliminate ac components from the results. The remaining dc components correspond to the amplitude of each order harmonics and the fundamental component in V_{out}. Following that, the outputs from the filters are compared with the references.

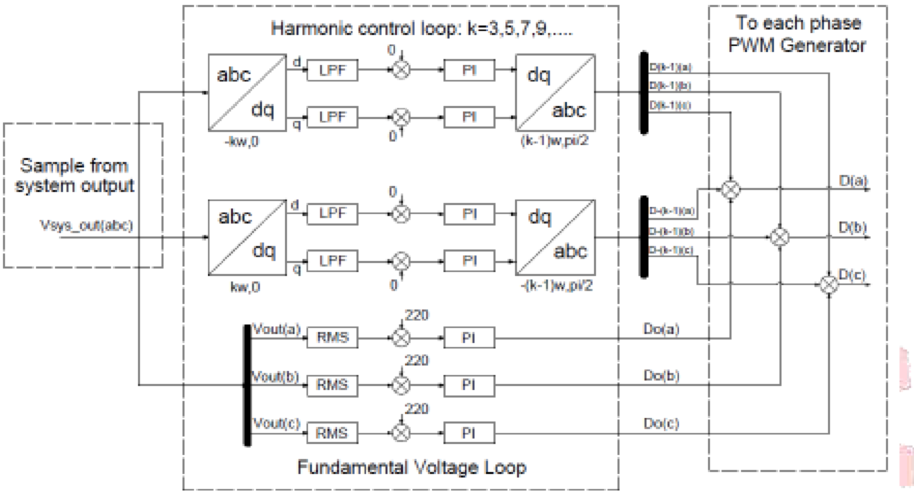

Figure 8. Closed loop control architecture of compensation system.

For the fundamental voltage regulation loop, the value from "d"-axis should always be zero and the "q"-axis value is compared with reference V_m. For the harmonics elimination loop, the value from both "dq" axes is compared with zero. Taking the reverse-feedback mechanism into account, the input of PID compensator should be connected as Figure 8 shows. After the comparison, the differences are sent to PID compensators that are utilized to generate the coefficient of D in "dq" form. Then, the coefficient from harmonics loop in "dq" form is transformed to "abc" form by applying Ipark's transformation. It should be noticed that particular even order harmonics are required in duty cycle D to eliminate the corresponding odd-order harmonics in V_{OUT}. Thus, Ipark's transformation matrixes with special frequency and angle are applied in the architecture, which is also given in Figure 8. Finally, the coefficients in "abc" form and the output from fundamental voltage loop are combined together to be the modulation waveform of D which is sent to each phase Direct AC-AC High Frequency Link circuit. All the outputs from the control loops are expressed in a three-phase form. The modulation wave for each phase is the output from each loop added together. With the injection of proper modulation signal, a series of compensation voltage out phase with the existing harmonics is generated by the converter circuit, counteracting the existing harmonics. The converter can also function to handle any voltage variation by controlling the coefficient K_0.

The relationship between the system input voltage $V_{sys\ in}$ and output voltage $V_{sys\ out}$ is given by

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

VI. SIMULATION PARAMETERS, RESULTS AND DISCUSSION

TABLE II.

PARAMETERS FOR PROPOSED SYSTEM.

$V_{sys\ in}$	220V
Switching frequency	10kHz
Ns:Np	12:1
Ci	3µF
Li	2mH
$V_{sys\ out}$	220V
Csi	1µF
Co	5µF
Lo	0.68mH

The system parameters used in proposed Direct AC-AC High frequency link converter is shown in Table 3. The computer aided simulations are performed to verify the effectiveness of the proposed sinusoidal pulse width modulation technique with the direct AC-AC high frequency link converter. Three 1mH inductors *Ls* are connected in series with the output of the three sine voltage sources in order to simulate a weak grid. Initially, the system is designed to eliminate the third, fifth, seventh, and ninth harmonics caused by the nonlinear load.

The simulation result of pulse waveform, three phase voltage and FFT spectrum of phase current of direct AC-AC high frequency link converter are presented in Figure 10-12. The simulation results for harmonics elimination are displayed in Figure 10.

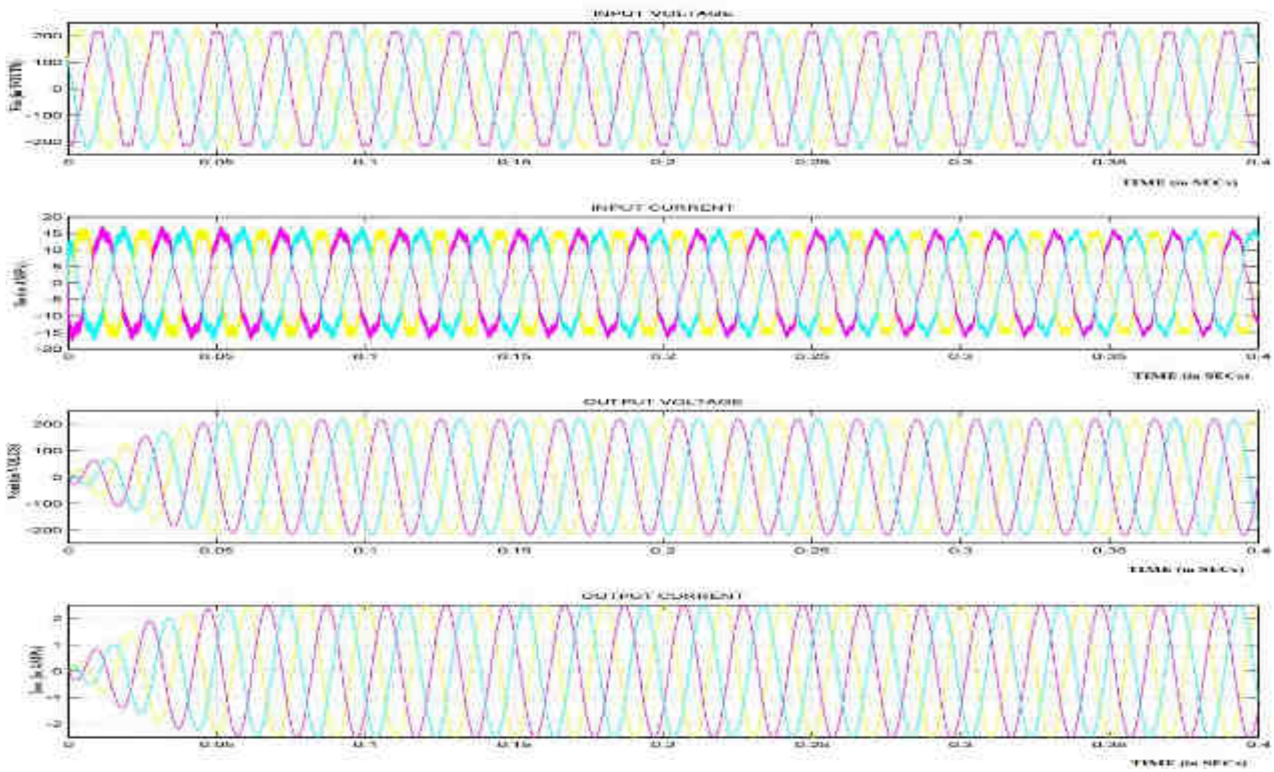

Figure 10. Simulation results of Voltage and current waveforms.

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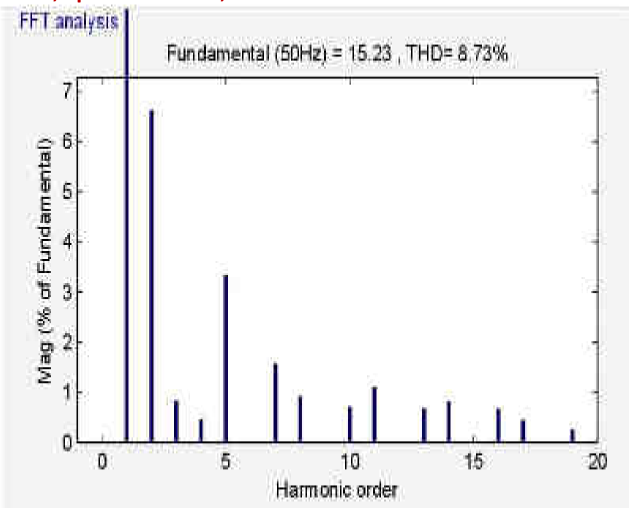

Figure 11. Harmonic analysis of input current

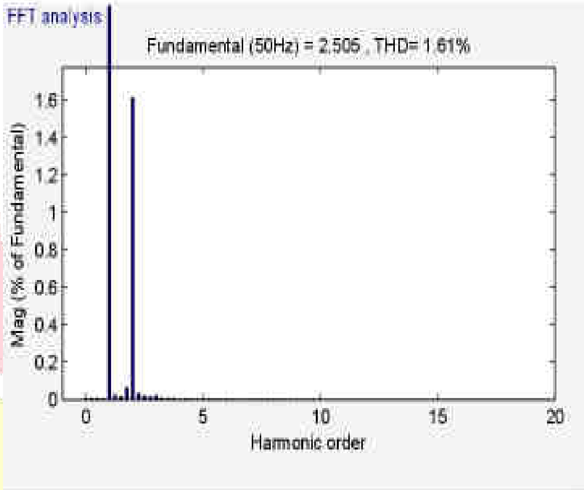

Figure 12. Harmonic analysis of output current

The distorted load current drawn by the non-linear load causes a distorted voltage drop in the cable impedance. The resultant distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them even if they are linear loads**.** The content of the harmonics in the output voltage are minimized by operation of the proposed converter, as shown in Figure 12. The results of FFT analysis of the input and output voltages are given in Fig. 11 and 12 respectively. Due to the non linears loads 5th, 7th, 11th, 17th order harmonics are generated in supply voltage when using direct AC-AC high frequency link converter higher order harmonics in output current are minimized. The current THD reduced from 8.73% to 1.61%, which shows the effectiveness of the direct AC-AC high frequency link converter used for unbalanced harmonics elimination.

From the analysis of the obtained results, the THD values have been considerably reduced as per the IEEE standards, when compared to the conventional system the voltage THD value is reduced from THD=10.1% to THD=1.98% and also the 5th , 7th , 9th and 11th order harmonics are minimized. By the proposed method the switching losses are also minimized.

VII. Conclusion

Direct AC-AC high frequency link converter is proposed in this work. The proposed converter which can transfer one unregulated sinusoidal voltage with high THD into another regulated sinusoidal voltage with low THD at same frequency. The proposed converter has simple topology, two-stage power conversions, bi-directional power flow, high frequency electrical isolation, good load adapting ability and good line current waveform. Direct AC-AC high frequency link converter with proposed modulation strategy can achieved AC voltage output with constant amplitude phase and frequency without any electrolytic capacitors. Thus, the system reliability is enhanced. Furthermore, the cost, weight and the size are reduced. The elimination of lower order harmonics is achieved using the proposed technique. Hence the THD value has been reduced compared to conventional converter with symmetric source. A simulation result shows the accuracy of direct AC-AC high frequency link converter. In future instead of using PI controller, fuzzy logic controller can be used to provide more accurate switching patterns in order to achieve better performance..

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