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VOLTAGE BALANCE CONTROL AND STABILITY OF A SYSTEM BY USING MODULAR CONVERTER WITH MULTIWINDING HIGH-FREQUENCY TRANSFORMER

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ABSTRACT: A modular H bride rectifier or also called as cascaded H bride converter with multi winding high-frequency (MWHF) transformer is proposed for medium- or high-voltage applications. In the proposed converter, a step down transformer is no longer require in place of this we can use high frequency multi winding transformer while a cascaded *H*-bridge rectifier (CHBR) is connected directly with the input ac source. Then by composing a group of *H*-bridge converters an isolated dc-dc converter is made and a MWHF (multi winding high frequency) transformer with high power density is used to isolate the dc buses produced by the CHBR. The mathematical model and equivalent circuit of the MWHF transformer and the high frequency (HF) converter are obtained in this paper. Then, the naturally balance ability and the voltage stability under unbalanced loads is analyzed and is verified. To accelerate the dc bus voltage balancing process, a voltage balance control algorithm based on energy exchange between different transformer windings is proposed that is realized by accomplishing the phase shift adjustment of the terminal voltages on different windings. Experiments and simulations are done to verify the performance of the proposed modular converter.

INDEX TERMS: *H*-bridge, high-frequency (HF) transformer, multilevel converter, voltage balance control.

INTRODUCTION:

For medium- and high-voltage applications, MULTILEVEL converters gain increasing attention because of the voltage limitations on unit power electronic devices. Many kinds of multilevel topologies are proposed, to simplify the control and improve the reliability. The first kind is neutral-point-clamped (NPC) converters where a lot of capacitors or clamping diodes are needed to balance the neutral point voltage, and with the increase of voltage levels, the number of clamping diodes and capacitors will increase significantly. **A**nother kind is cascaded H-bridge converter that is modular type converter and the clamping devices are not necessary. An industrial-frequency multi winding isolated transformer is needed to produce the balanced voltage and isolated for the cascaded modules. The cost and volume of the whole converter is increased with respect to the transformer. Some novel converter topologies are studied to reduce the system cost and volume, to increase the power density, and also to increase the stability by modular design. The modular design can also simplify the converter structure and increase the fault operation capacity. In a transformer-less multilevel converter is proposed whose outputs in each module are not isolated. In this case, the output can only be connected with loads of multiphase motors or separate motors. The dc voltages are difficult to be balanced while the loads are unbalanced.

To realize isolation in the converters, the medium or high-frequency (HF) transformer is used. The transformer working on higher frequency is of high power density compared to the industrial-frequency transformer. The methods for the reducing switching loss and control and in the converter with high frequency transformer have been studied. It is difficult to be realized that the converter proposed needs a high-voltage ac–ac converter. The converter topology proposed by Akagi attracted a lot of researches, which is modular since the H-bridges are used for both the HF converters and high-voltage rectifier. In the topology proposed, the load unbalance will worsen the voltage balancing of the converters. So it can be cascaded again to feed one load only or it can feed balanced loads. Otherwise, the dc bus on the secondary side must be connected in parallel to keep voltage balance when feeding isolated unbalanced loads. The converters with high frequency transformer have also been studied for the applications such as in tractions that need higher power ratings. A lot of researches have been studied and implemented for the modulation methods for the HF converters and for the voltage balance control. The multi winding high frequency transformer is used for the energy balance and isolation. The windings linking the same flux can realize energy exchange, which can be used to balance the voltage and the load energy. So the voltage equalization can be realized easier.

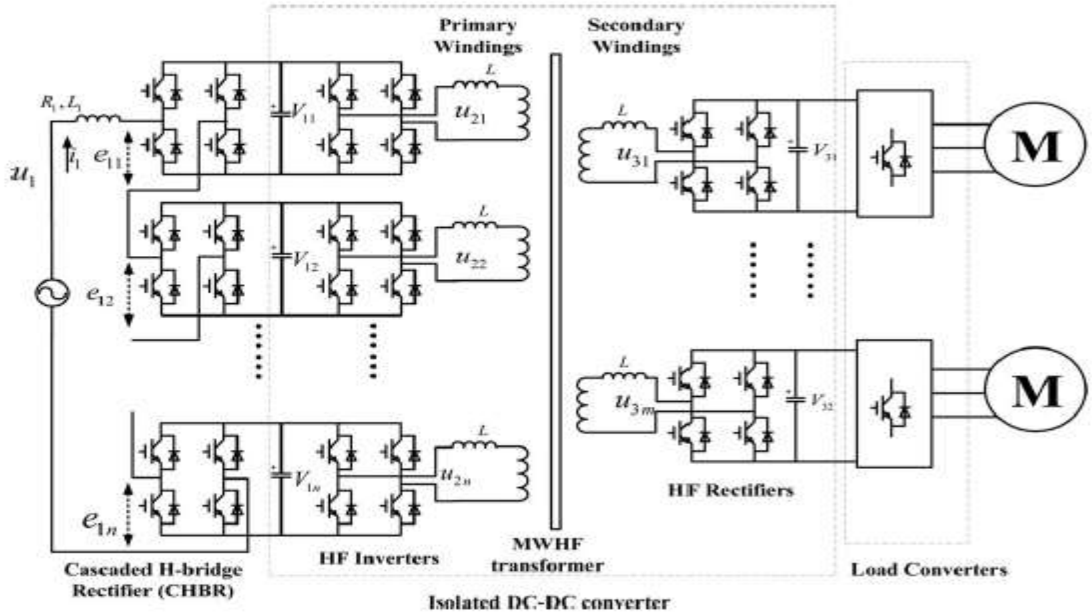

Fig. 1 General topology of proposed converter

In this paper, a novel modular multilevel converter is proposed where a multi-winding high-frequency (MWHF) transformer is used for the isolation and voltage balance. The cascaded H-bridge rectifier (CHBR) can be connected directly with the input ac voltage without need of the step-down transformer, this reduces the cost of extra step down transformer.

2. CASCADE H-BRIDGE MULTILEVEL CONVERTER

Cascaded H-bridge or also called CHB converters consist of H-bridge converters that are connected in series in each phase of the converter. From fig. 1 The AC-side output voltage of the single-phase leg of the converter v_{cA} is the sum of the output voltages of both H-bridge converters $v_{cA} = v_{cA1}+v_{cA2}$.One of the most commonly used pulse width modulation methods for CHB multilevel converters is the space vector pulse width modulation (SVPWM). The SVPWM method for the single-phase leg of the converter is illustrated in Fig. 2. In the PSPWM method the switching signals $s1$, $s4$, $s5$ and $s8$ are produced by comparing the modulating signal S_M, which is characterised by the

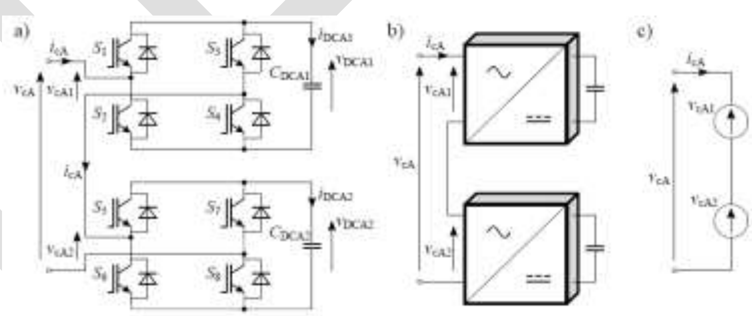

Fig. 2: Single-phase leg of the five-level cascaded H-bridge converter: a) the power part circuit, b) the block diagram, c) simplified circuit

amplitude A_M and frequency f_M, with uniformly phase-shifted triangular carrier signals S_{N1}–S_{N4}, which have the same peak values A_N and the carrier frequency f_N. The carrier frequency determines the switching frequency of transistors, thus $f_S = f_N$. Other switching signals ($s2$, $s3$, $s6$ and $s7$) are complementary to signals $s1$, $s4$, $s5$ and $s8$ respectively. Similarly to other PWM methods, two modulation indices can be defined for the PSPWM method. They are the amplitude modulation index $m_a = A_M/A_N$ and frequency modulation index $mf = fN/fM$. One can see from Fig. 2 that switching signals affect the output voltages vcA1, vcA2 and DC - link currents iDCA1, iDCA2, which can be expressed by these two equations respectively.

$$v_{cA1} = v_{DCA1}\left(s_1 - \overline{s_4}\right),\ v_{cA2} = v_{DCA2}\left(s_5 - \overline{s_8}\right)$$
$$i_{DCA1} = i_{cA}\left(s_1 - \overline{s_4}\right),\ i_{DCA2} = i_{cA}\left(s_5 - \overline{s_8}\right)$$

The effective switching frequency in the H-bridge converter output voltage vc Ax is two times higher than the switching frequency fS (Fig. 2b) [1]. Since the output phase voltage vcA is the sum of voltages vcA1 and vcA2, vcA = vcA1+vcA2, the effective switching frequency observed in the output voltage of the five level CHB converter is four times higher than the switching frequency fS. This means that in each switching period TS there are four pulses which have the same width and are uniformly distributed. The effective switching frequency increase is one of the most important advantages of the CHB multilevel converter and allows using smaller reactive filters in the AC-side of the converter.

CONFIGURATION OF CASCADED H-BRIDGE RECTIFIER:

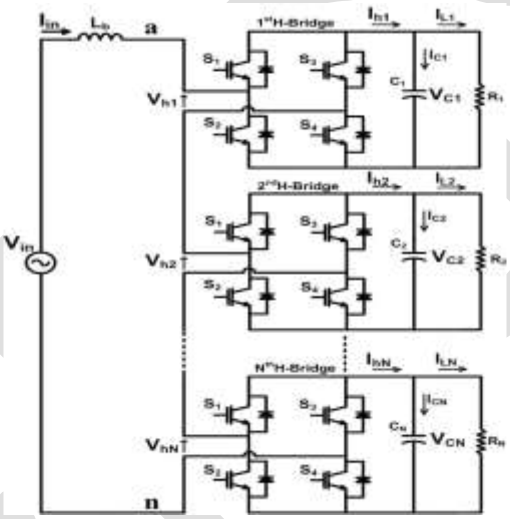

Fig. 3 Bidirectional CHB rectifier with N H-bridge cells.

A CHB converter is the best choice for working in high voltage and high-power applications due to its extreme modularity, simple physical layout and low losses

2.1 SELF-BALANCING ABILITY OF THE CONVERTER

In the proposed circuit, the multi winding high frequency transformer has the functions of isolation and energy balancing ability between each cell. The control of the high frequency or HF converters is the most important part of the control of the entire isolated dc/dc converter. In medium- or high-voltage applications, the switching frequency of the devices is limited while a high-frequency voltage is needed by the MWHF transformer. So square-wave modulation is usually used in this kind of converters. The square wave voltage input to the windings can be shown in Fig. 4. A 50% duty symmetrical square wave is used to approach the fundamental sinusoidal wave and to reduce harmonics. If the switching frequency is much higher than the output voltage frequency, such as in using high speed MOSFET or SiC devices, the sinusoidal modulation can also be adopted. To get larger flux and higher efficiency, all input voltages on the transformer windings are controlled to keep almost the same phase. The stability and voltage self-balance ability of the circuit will be analyzed in this section.

3. ISOLATED DC-DC CONVERTER

In DC-DC converter again it is devided into three main parts,

1. HF (high frequency) inverter.
2. MWHF (multi winding high frequency) transformer.
3. HF (high frequency) rectifier.

The proposed converter is shown in Fig. 1. There are three parts: the first is a cascaded *H*-bridge rectifier (CHBR) which is used to convert the input ac voltage to the cascaded dc buses. Because of the little limitation on cascaded levels, the CHBR can be connected with the grid voltage directly without using of step down transformer. The second part is an isolated dc–dc converter with an MWHF transformer, which is of higher power density than an industrial-frequency transformer. A group of *H*-bridge converters together with the transformer windings are used to convert the dc voltages to HF ac voltages, or convert the HF ac voltages to dc voltages. To be convenient, the HF converters connected with the primary windings of the transformer are named as the HF inverters while the ones connected with the secondary windings are named as the HF rectifiers. The third part is load converters to feed all kinds loads with different voltages and powers.

In the proposed converter, the unbalanced load may result voltage difference at the dc buses and will affect the stability of the converter. And the self-balancing speed is limited by changing the circuit parameters. So the voltage balance control method need to be studied to accelerate the voltage balancing and to eliminate the voltage difference caused by the power imbalance.

Supposing that the number of cascaded modules of the CHBR is n, which is the same as the number of the primary winding of the transformer. The number of the secondary winding is m. The total number of the transformer windings is $N = n + m$.

By energy balance principle, the state equation of one dc bus voltage is shown in (24)

$$\frac{d}{dt}\left(\frac{1}{2}CV^2\right) = P_i - P_o$$

Where V is the dc bus voltage, C is the value of capacitance, Pi and Po are the instantaneous input and output powers on the dc bus. Po also equals the power input into the transformer windings if ignoring the converter losses. The filter inductance can be regarded as a part of the leak inductance of the transformer.

The average value of the dc bus voltage is affected by the active power input to the dc capacitor. And the fluctuation of the dc bus voltage is affected by the reactive power. It means that the dc bus voltage can be realized by adjusting the active power injected into the dc capacitor.

Since the carrier phase-shift PWM is used in CHBR, the active power input to each dc bus is fixed. The load power of the converter is determined by the loads. So the dc bus voltages can only be controlled by the active power flow from the dc buses to the transformer windings that can be controlled by the HF converters associated with the multi winding transformer.

In the multi winding transformer, all terminal voltages of the windings must have the same frequency to reduce the loss and harmonics. All windings are linked by the same flux if ignoring the leakage flux. The power can be transferred between the windings through the common flux, which can be used for the voltage balancing control. The energy exchange method will be studied in this section.

The state equation in each winding of the transformer is

$$u - e = Ri + L\frac{di}{dt}.$$

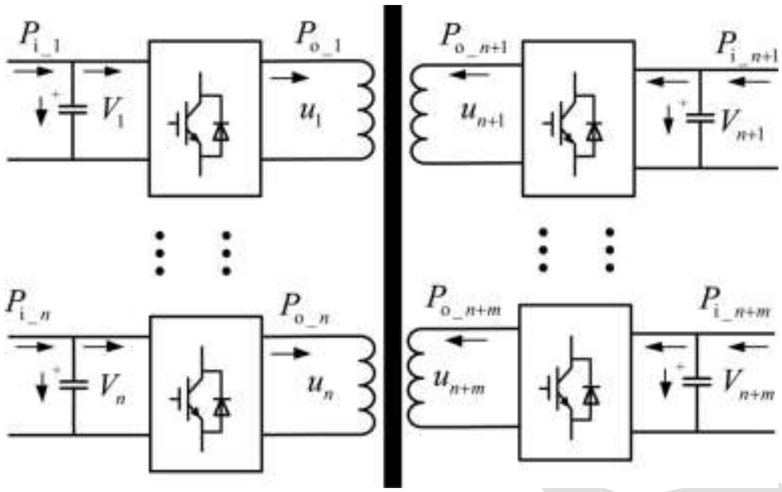

Fig. 4 Power flow between all windings.

Here *u* is the terminal voltage of the windings. Variable *e* is the back EMF produced by the flux. *R* and *L* are the resistance and inductance including the leak inductance of the winding and the filter inductance between the converter and the transformer. If ignoring the differences between the windings of the transformer, the back EMF and impedances are all the same. Then, the state equation of all windings can be shown as

$$\begin{cases} u_1 - e = Ri_1 + L\dfrac{di_1}{dt} \\ u_2 - e = Ri_2 + L\dfrac{di_2}{dt} \\ u_{n+m} - e = Ri_{n+m} + L\dfrac{di_{n+m}}{dt} \end{cases}$$

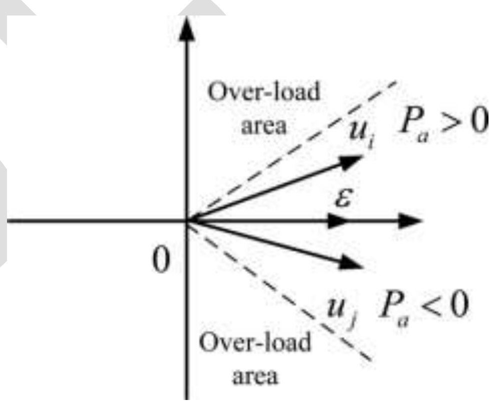

Fig. 5 Output power control by phase adjustment.

So the power flow between the windings is determined by the fundamental component whose phase is also the same with the symmetrical square wave. That means the active powers are also determined by the phase of the square wave voltage.

4. LOAD CONVERTERS

A load converter is a IGBT controlled inverter. Again the dc voltages are inverted to ac voltages at required level using inverter and connected to different loads to feed all kinds loads with different voltages and powers.

VOLTAGE BALANCE CONTROL:

We can see that if there is no phase difference between the terminal voltage and back EMF, the output active power of this winding will be zero even if there is an amplitude difference. It means that only phase of the terminal voltage can be used for active power control.

To be simple, the same modulation method is used for all HF inverters and HF rectifiers in the isolated dc–dc converter, except the difference of phase. So all the terminal voltages of the transformer windings have same amplitudes when the dc buses are balanced. As in the former analysis, the dc bus voltage can be adjusted by the re-distribution of the input and output power between the transformer windings, which can be realized by the adjustment of the phase angles of the terminal voltages.

Here *U*and *I* are the rated voltage and current of the windings. If the phase difference increases, the current and power passing the winding will increase quickly and overload will occur that will damage the transformer and converters. As the increase of the reactive power, the fluctuations of the dc bus voltages will increase, which will reduce the performance of the converter. So the phase difference is normally controlled to be little difference to avoid over-current and over-load, as shown in Fig.

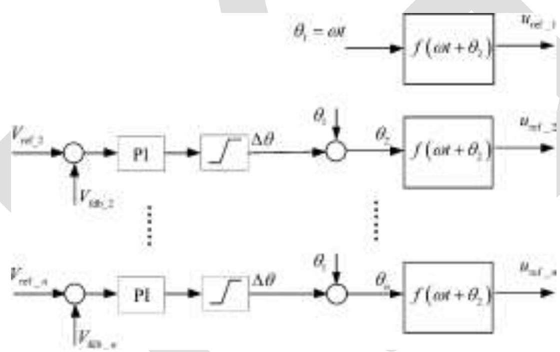

Fig. 6 PI regulators to get the control phase angles.

Because the summarized dc bus voltage connected with the CHBR is already controlled by the control scheme shown in Fig., only $n + m - 1$ dc buses are needed to be controlled directly by separate voltage balance controllers. These $n + m - 1$ dc buses are named directly-controlled dc buses. The last one can be balanced naturally if the summarized dc buses voltage and the $n + m - 1$ buses are all controlled well. So it can be named as indirectly-controlled dc bus.

The voltage difference is nonlinear with the phase difference angle, also the angle of the back EMF is difficult to be got directly, so a PI regulator for the dc voltage feedback is used where the phase difference with the back EMF is adaptively obtained. In practice, the output voltage phase on the first dc bus $\theta 1$ is used as a reference. Then, a group of PI regulators are used to get the phase angle of the terminal voltages on the other windings. The difference of the dc bus voltages and their reference values are used as the input of the PI regulators, as shown in above Fig. The output is the phase difference to the first cell.

By the adaptability of the PI regulator, the difference between the windings, such as the back EMF and impedance difference, can be compensated by the close-loop control.

SIMULATION IN MATLAB ENVIRONMENT:

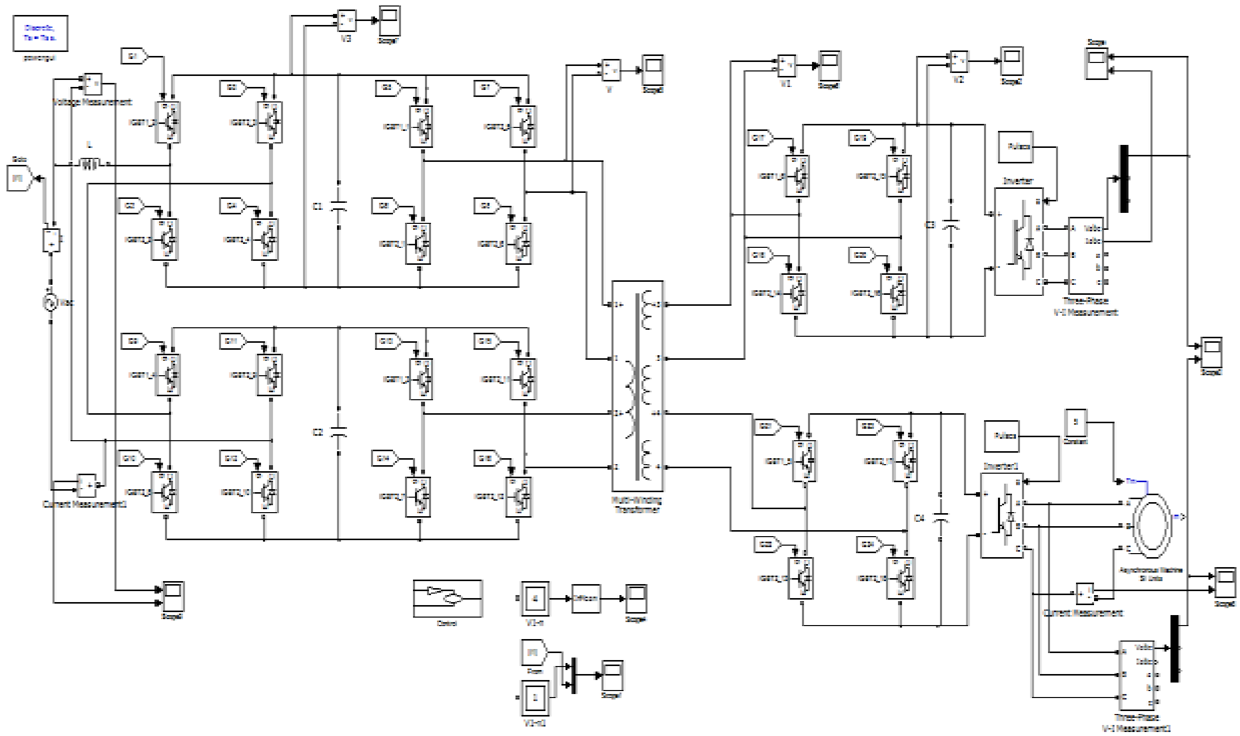

Fig.7 Simulating circuit diagram

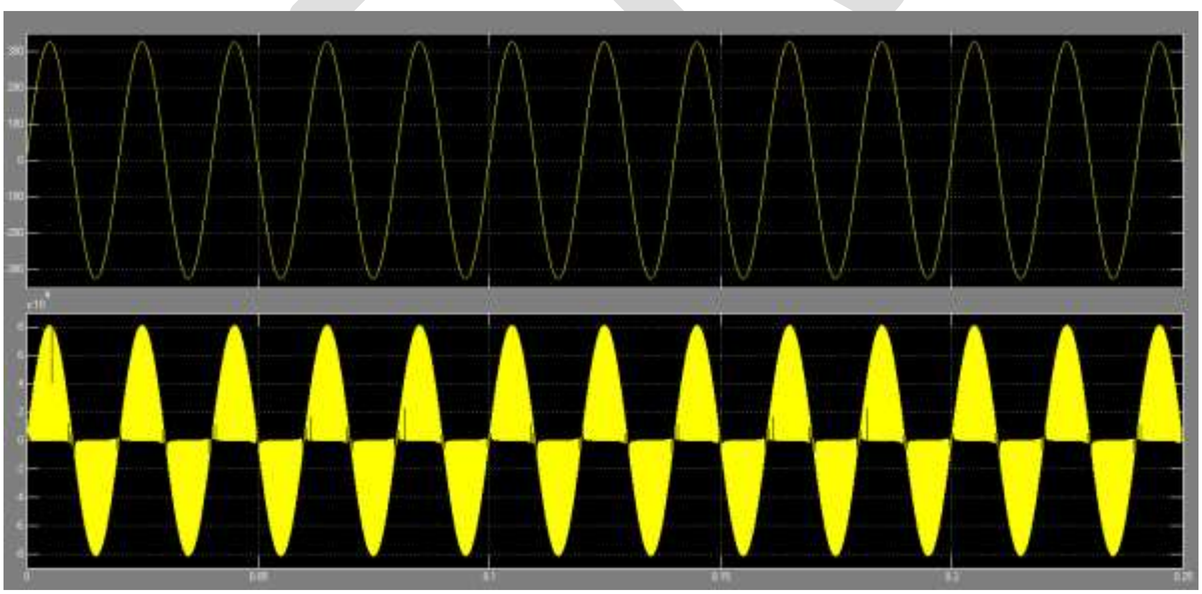

Fig.8 Input voltage and current

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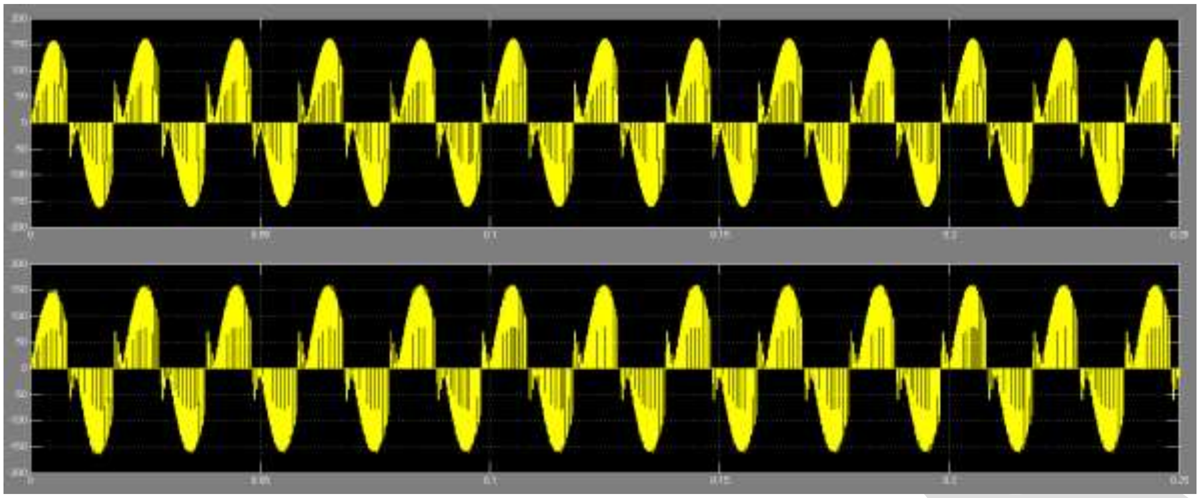

Fig.9 Output voltage at no load and full load

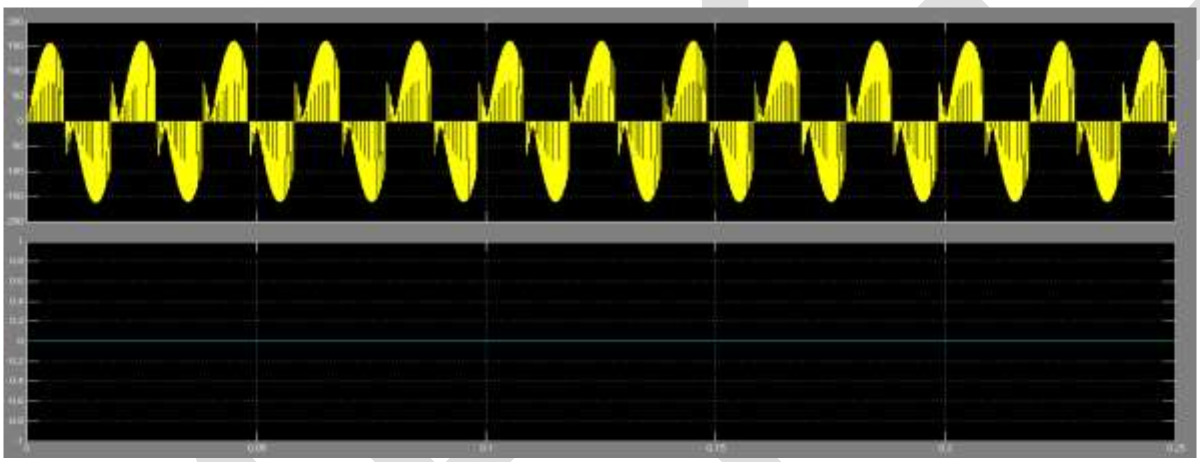

Fig.10 Output voltage and current at no load

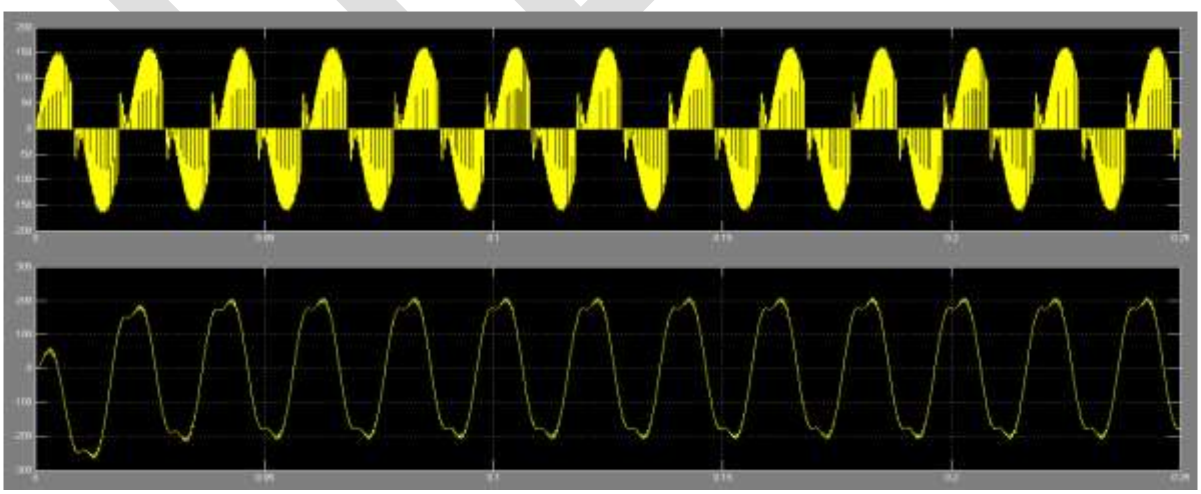

Fig.11 Output voltage and current at load (induction motor).

CONCLUSION:

The proposed modular type multilevel converter can be applied for medium or high-voltage applications. In this modular converter the high frequency transformer decreases the system weight and volume compared with the generally using industry-frequency transformer. The high frequency multi winding transformer can also realize the voltage balance control and the power redistribution but not effecting other connected load. It is modular and is of the characteristics of high reliability. A voltage balancing control method based on terminal voltage phase adjustment is studied in this paper. Simulations and experimental have been implemented and tested to verify the stability without control. It shows that the proposed experiment can be controlled stable and reliable under unbalanced (varying) loads and the proposed voltage balance control waveforms is also verified.

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