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Research on a New Type of Energy Feedback Cascade Multilevel Inverter System

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Abstract

Traditional cascade multilevel inverter can only transmit one-direction of energy. This paper proposes a new cascade multilevel inverter topology and control strategy based on part units to realize the energy feedback. By using PWM converter to replace uncontrollable converter in part units of the traditional inverter, and combining the inverter with H-bridge inverter, the two-direction running of the cascade inverter is realized. A double closed loop control strategy is used to obtain fine control characteristic of input current. The carrier phase-shifted SPWM technology is adopted in the cascade inverter to reduce harmonious wave of output voltage and current, meanwhile, a new type of bypass control method is proposed to collect all the feedback energy and restore it into the energy feedback units. According to the simulation of a three-phase and five-unit cascaded inverter with three energy feedback units, the results demonstrate that the proposed inverter can be input near sinusoidal current , and realize two-way flow of energy automatically with simplified phase shifting transformer structure, and show its feasibility and effectiveness.

***Keywords**: cascaded inverter; partial energy feedback; PWM rectifier; CPS-SPWM*

1. Introduction

Cascaded multilevel inverter has become increasingly popular in recent years, especially in the field of motor speed adjustment in high-voltage with high-power balance situations, as it can solve the drive problem in high voltage motor by low voltage, and extend the voltage class easily with low harmonic content in output voltage, simple control strategy and outstanding energy conservation.

The traditional topological structure of cascaded multilevel inverter is shown in Figure 1, which consists of phase shifting transformer and a number of power units with the same structure. The internal structure of the power unit is shown in Figure 2. The input side is the uncontrollable three-phase bridge rectifier composed of diodes. When induction motor is in the process of braking or downing potential energy load, it will be in renewable state, meanwhile, the mechanical energy of transmission system is transformed into electrical energy by generator, and then stored into the direct current capacitor through freewheeling diode of the power units of each H Bridge in the output side of the inverter. Because of the uncontrollable rectifier, energy only flows one-way, and it will lead to the increase of the voltage in the direct current side, and the pumping-up voltage [1], which could give rise to the overvoltage protection of inverter or even the overvoltage damage to the high-power units in main circuit if the inverter fails to release the energy in time [2]. Mass of harmonic wave exist in the input current due to uncontrolled rectifier, which pollutes harmonic to the grid enormously [3], and phase-shifting transformer could complicate the system design. These issues confine its use in the field which requires two-way flow of energy such as rolling mill, electrical traction and so on [4,5].

At present, there are several methods to tackle renewable energy: Dissipation in the braking resistance with multiple direct current side and capacitor, this method features simple structure and easy to perform, but wastes quite a lot of energy and have some side effects under some circumstances [6]. Add independent energy feedback bypass in each unit, which can save energy enormously, but complicate the system structure at the same time [1, 7].Topology of main circuit with double PWM, which transforms the uncontrollable diode rectifiers into PWM rectifiers [8, 9], which can realize renewable energy feedback to the power

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grid efficiently, but this method requires more power devices and it is difficult to control and with higher costs.

Based on these issues discussed above, this paper proposes a new cascade multilevel inverter topology, which has some uncontrolled diode converters and fully controlled PWM converters through which all the regenerated energycan feedback to the power grid. The energy flows in two-way automatically and efficiently in a brief structure, and the input/output harmonic contents are reduced greatly, which can reduce the pollution to the quality of the electric energy in grid and expand the application of cascaded inverter. The result of the simulations demonstrates the feasibility of this novel topology and control strategy.

2. Cascaded inverter topology with partial units energy feedback

The new cascade multi-level high voltage inverter proposed in this paper is implemented based on the improvement of each power unit in traditional inverter, and its main circuit topology is same as Figure 1. The main idea is substituting three-phase PWM Rectifier Bridge which is consisted of full-controlled power components for uncontrolled bridge rectifier for partial power units, and the H bridge inverter remains unchanged. The topology is shown in Figure 3, which consists of filter inductances, PWM Rectifier Bridge, energy storage capacitance and H bridge converter, and other components are the same as Figure 2. Based on the topology shown in Figure 3 and the control strategy of PWM converter, the outstanding input current control characteristics and two-way energy flow of power units can both be achieved. Energy feedback inverter is composed of power units with their input end parallel and output end cascaded. The number of energy feedback power unit will be determined by the value of the feedback energy and the capacity level of power unit. Explaining research chronological, including research design, research procedure (in the form of algorithms, Pseudocode or other), how to test and data acquisition [1, 9]. The description of the course of research should be supported references, so the explanation can be accepted scientifically [9, 10].

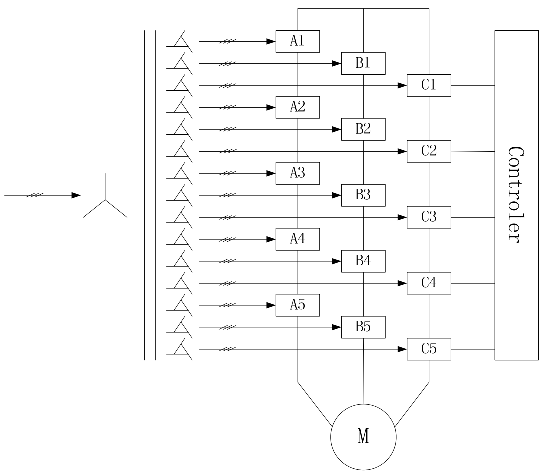


Figure 1. Topology of traditional cascade multi-level inverter

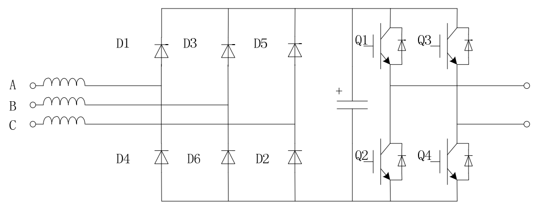


Figure 2. Topology of traditional power unit

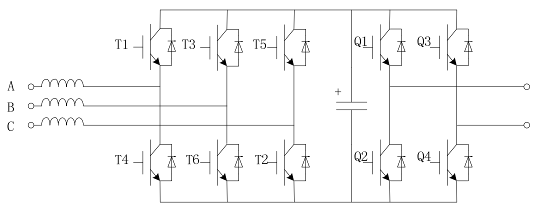


Figure 3. Topology of energy feedback power unit

Figure 4 demonstrates an example of the proposed single-phase topology structure of inverter, which is composed of 5 cascade units with 3 feedback units. The input side of the middle three units utilize three-phase PWM rectifier, which enables energy feedback, and the rest two units still use uncontrolled rectifier bridge composed of diodes.

When energy flows in the forward direction, not feedback energy unit works in the mode of uncontrolled rectifying circuit, while feedback energy unit adopt the control policy of PWM rectifier, which enables the stability of voltage and the flow of current in the forward. On the contrary, when there is energy feedback, some measured must be taken to gather the energy to the capacitor of feedback power unit, and finally to the grid according to Three-Phase PWM rectifier. The control strategy and the running features will be detailed in the next chapter.

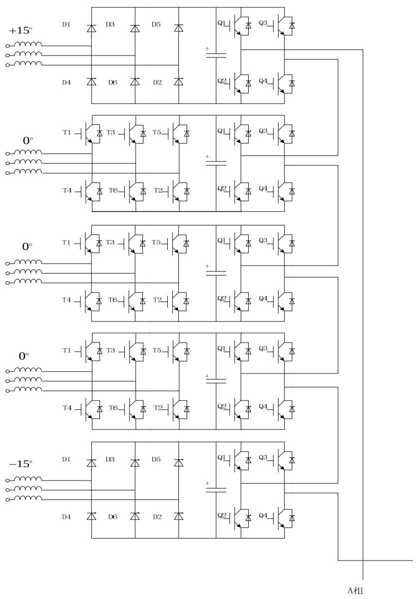


Figure 4. Topology of five units cascade multi-level inverter with single-phase three feedback unit

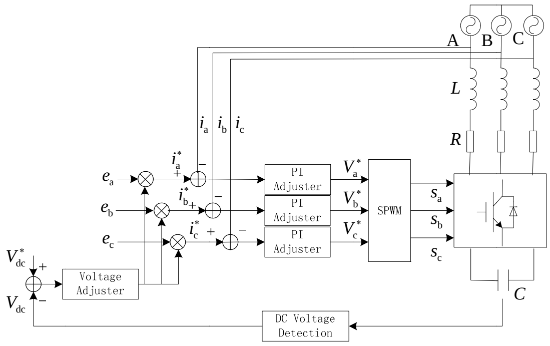


Figure 5. Control strategy of three-phase PWM rectifier

3. Control policy of cascade inverter with partial unit energy feedback

According to the features of cascade inverter with partial unit energy feedback, the inverter can be divided into two parts, input PWM rectifier and output H Bridge inverter, both of them can be controlled independently.

3.1. Input PWM rectifier bridge control

As for the energy feedback unit, each input end of the power unit has the same structure and mutually independent, thus, it is enough to illustrate only one policy of PWM rectifier, and its purposes are as follows:Input current in Sine shape.The phase control of input voltage and input current, and maximum power factor is the main target, ideally, the input voltage and current are in the same phase or anti-phase.The voltage of DC bus keep permanent Two-way energy flow automatically.

Figure 5 is the frame of PWM rectifier with three-phase topology structure, which utilize double-loop controlstrategy: DC bus voltage outer loop and input current inner loop [11].

In Figure 5, after comparison of the direct current output voltage $\mathbf{V_{dc}}$ and the given reference voltage V_{dc}^* , $\mathbf{V_{dc}}$ is transmitted to the PI regulator. The output of voltage control race i^* is considered as the given value of grid current amplitude. This given value multiplied e_a 、 e_b 、 e_c respectively, which are unit sine signal with the same phase as the electromotive force of grid current, and the instruction values i_a^* 、 i_b^* 、 i_c^* in three-phase grid current are obtained. After the comparison of the instruction values with the feedback values i_a , i_b , i_c in three-phase grid current, the instruction values are transmitted to the current PI regulator. After being modulated by SPWM, the output of current PI regulator can generate control pulse, and realize the control of the main circuit.

Meanwhile, the input current of PWM rectifier has sine shape; the harmonic content is quite low, and there is no need to shift the phase of secondary side winding in input end transformer. These methods can simplify the design of phase-shifting transformer and reduce the cost.

3.2. Output H bridge inverter control

The technology of CPS-SPWM carrier phase shifting is particularly suitable for cascaded multi-level inverter[6]. The pulse signal of each SPWM is generated by comparison of triangle carrier and sine wave modulation. Each phase adopted the same sine wave modulation and phase shifting angle exists between the adjacent carrier wave, which enables SPWM pulse generated in each unit has the same base wave phase and amplitude, but the pulse does no overlap, so multi-level voltage waveform is obtained after superposition of each phase, and the equivalent switch frequency is improved greatly. Thus, the output of harmonic wave can be decreased without increasing switch frequency. The best phase shift angle has been analyzed in [5] with the conclusions:

$\theta = \frac{180}{N}$, whereN is an even number

$\theta = \frac{180}{N}$ or $\frac{360}{N}$, where N is an odd number

In order to obtain the optimal harmonic eliminate effect, this paper adopts the modulation strategy that combines the double change and level carrier shift phase modulation [12], which means each H bridge inverter use two road triangle carrier wave C_L, C_R with opposite phase and the same modulation wave to generate PWM waveform. Four road PWM signals are generated after reversing the waves, and they can be used to control the power unit in both left and right bridge arms in H bridge inverter, and achieve the output of tri-level voltage. According to the method, the number of voltage level output from inverter is:

$$M_p = 2N + 1$$

The equivalent carrier wave frequency of the output voltage of the entire inverter is 2N times that of cascade unit carrier wave, which can reduce the output voltage and current harmonic, wave efficiently, and remain the amplitude.

Not all the units in the proposed inverter can realize energy feedback, thus how to gather the energy that distributes in the direct voltage of each cascade unit to the energy feedback unit is of vital importance, and it is necessary to research the distribution of renewable energy in each power unit, and provide guidance for the system design.

There are four working states in the circuit: forward direction conducting, reverse direction conducting, forward direction bypass and reverse direction bypass. The concise circuit model of N unit cascade inverter when its load is in the state of renewable electricity generation is shown in Figure 6 (a). A group of mutually isolated direct capacitors are cascaded with N equivalent switches, and the position state of switch determines whether the direct capacitor stores the renewable energy [4].

In Figure 6 (a), the four power units in each H bridge inverter are replaced with a two state switch S_N'. When S_N' is in the left side, direct capacitor is connected to the main output loop store the renewable energy to the capacitor, and when S_N' is in the right side, direct capacitor is not connected to the main output loop, and the H bridge inverter is in the free-wheeling state, and provide only one loop. The output end of the power units are cascaded, thus the power units have the same renewable current at the same time when the load is transformed from motoring state into electricity generation state, which means each power unit are in the energy feedback state simultaneously. Meanwhile, the PWM technology based on carrier shifting phase theory features automatic energy balance [13]. Because each equivalent switch has the same fundamental waveand has the same duty ratio in a switch cycle when the load is in electricity generation state, the renewable energy stored in each capacitor is the same.

The novel control strategy proposed in this paper is that all the inverter unit IGBT are driven normally and they are working in the same mode as traditional cascade multi-level inverter when the generator is working. When the generator is in the renewable electricity generation state, the energy flows from the motor side to direct current side in inverter, and the direct voltage of five unit are increasing [9]. In order to gather all the energy to the energy feedback unit, the control strategy of non-feedback unit H Bridge should be modified, and the modified strategy is checking the direct bus voltage of non-feedback unit. When the voltage surpasses the given V_{dH} value, the driven information should be modified and make the non-feedback unit H Bridge is in the bypass state, then the energy can flow to the direct voltage of feedback power unit, and finally to the grid via PWM rectifier.

a The traditional control lower league inverter equivalent simplification model

b A new control lower league inverter equivalent simplification model

Figure 6. Cascade inverter equivalent simplification model

The principle of calculation and selection of parameter in pumping voltage suppression circuit [7] is that the pumping voltage must lower than that of the main circuit capacitor and high power unit, the upper bound is about $130\%\ V_{dc}$, where V_{dc} is the voltage of capacitor in normal working condition, thus voltage V_{dH} in non-feedback unit bypass selected in this paper is $130\%\ V_{dc}$.

Figure 6 (b) shows the H Bridge inverter side of the novel cascade multi-level inverter when energy back feeds. The inverter has 5 cascade units, and the middle 3 can realize energy feedback.

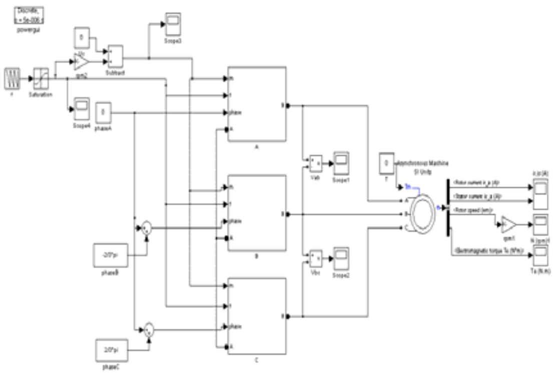
4. Simulation results

In order to verify the feasibility of the proposed topology of inverter and control strategy, a simulation model is established in Matlab/Simulink, and the multi-level high voltage inverter with three phase five unit cascade and three unit feedback that is applied in the frequency control of motor speed of 6KV high power motor.

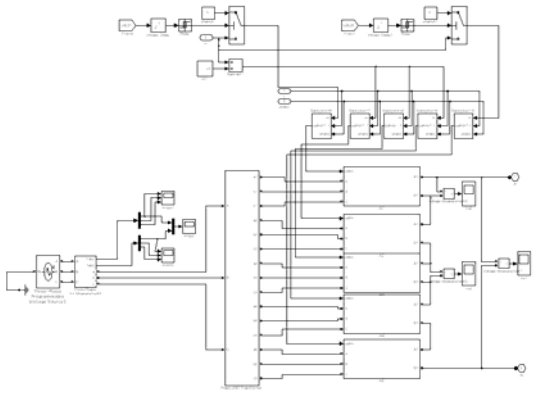
The parameters in the simulations are: the effective voltage value of three phase main input wire $E_{AL} = E_{BL} = E_{CL} = 6000V$; the input voltage frequency $f_e = 50HZ$; the effective voltage value of power unit input wire $u_l = 1000V$; filtering inductances: $L = 5mH$; direct current filter capacitor: $C_{dc} = 10000\mu F$, bus bar voltage $U_{dcref} = 1400V$; the upper bound of non feedback unit bypass is $V_{dH} = 1800$; PWM rectifier carrier frequency: $f_{cPWM} = 10KHZ$; H bridge inverter carrier frequency: $f_c = 1350HZ$; nominal power of motor $P_n = 1120KW$; nominal line voltage $V_n = 6000V$; nominal frequency: $f_n = 50HZ$; Pole logarithm: $P = 1$.

Figure 7 (a) is the simulation of the structure of 6KV cascade multi-level high voltage inverter. A、B、C are three phase module and each module is composed of phase-shifting transformer and five power units, as shown in Figure 7 (b), where A1, A5 are non-feedback power units with inner structure shown in Figure 7(c), and A2, A3, A4 are energy feedback power units with inner structure shown in Figure 7 (d).

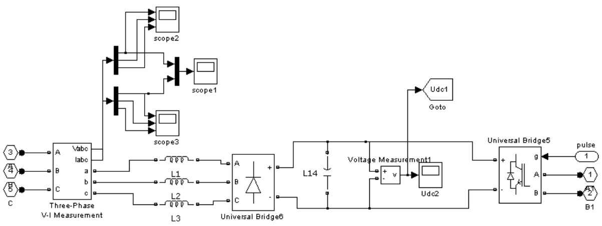
Simulation is conducted to analyze the performance of traditional cascade inverter, and observe the features of traditional inverter from the state of electricity regeneration in the process of frequency conversion braking. The motor is working in rated speed from beginning to the first second, then, it becomes linear frequency reduction brake, and the speed adjustment is constant V/F control. The frequency reduces to 0 at 9 second, which is the end of the speed reduction, and the simulation lasts 10 seconds.



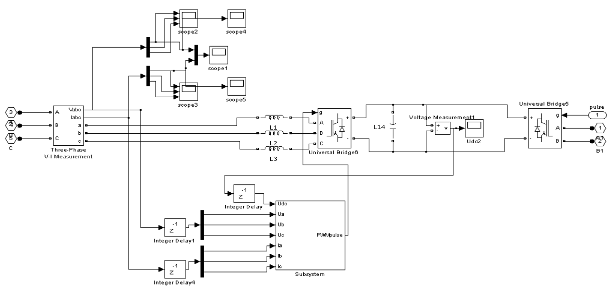
a New cascade multilevel high voltage inverter simulation overall structure



b New cascade inverter single-phase module simulation model



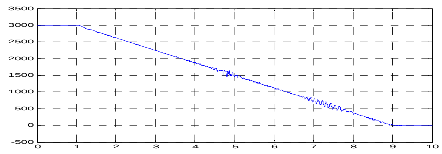
c Non-feedback of the power unit interior structure



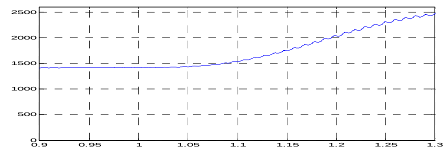
d The power unit energy feedback internal structure

Figure 7. New cascade multilevel inverter simulation structure

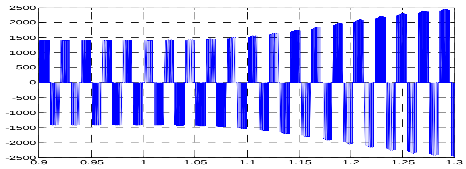
Figure 8 (a) is the wave form of motor speed, and the horizontal ordinate is time axis with second as unit, and the vertical ordinate is rotate speed with round per minute. At beginning, the motor is working with nominal speed 3000r/min, and brake 1 second later, the motor is in the state of electricity regeneration. Figure 8 (b) shows the waveform of bus bar voltage of power unit, and the horizontal ordinate is time axis with second as unit, and the vertical ordinate is voltage amplitude with voltage as unit. The energy cannot be fed back to grid when the motor is braking and bus bar voltage is pumping more than 70% in 0.3 second. Figure 8(c) and (d) are the output voltage of H Bridge inverter in power unit and phase voltage of 5 unit inverter respectively, and have the same axis as Figure 8(b). It can be learned from Figure 8(c) and (d) that inverter cannot work normally as the pumping of bus bar. Figure 8 (e) shows the unit input electricity of inverter (amplified 10 times), and the horizontal ordinate is time axis with second as unit, and the vertical ordinate is voltage amplitude with voltage as unit. The frequency analysis of electricity is shown in Figure 8(f), and the horizontal ordinate is frequency with HZ as unit, and vertical ordinate is the content of each harmonic wave, and it can be learned from the graph that the input current wave form is distorted greatly in uncontrollable diode rectification, and have rich low order harmonics, among which 5 harmonic wave is 74.9% of basic wave, and the ratio of total harmonic distortion THD is 101.13%, which would pollute the grid enormously.



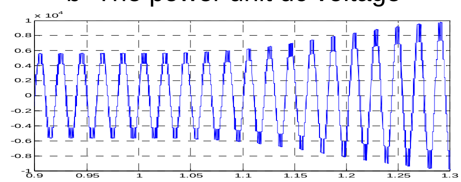
a Motor speed



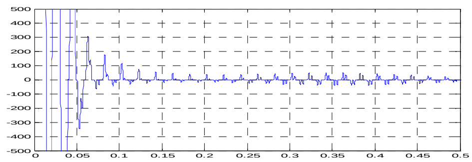
b The power unit dc voltage



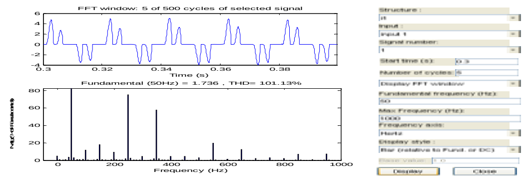
c The power unit H bridge converter output voltage



d Five unit inverter output phase voltage



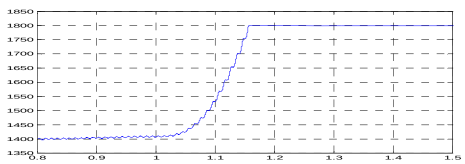
e The power unit to the input current (enlarge 10 times)



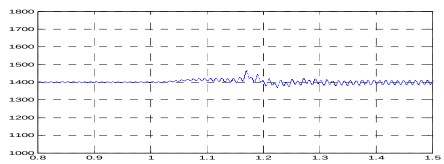
f Input current harmonic

Figure 8 Simulation waveforms of traditional cascaded inverter

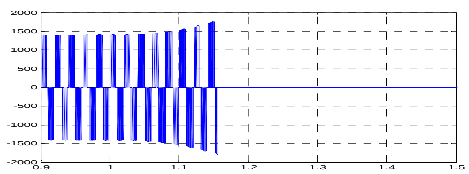
Aiming at the shortcomings of traditional inverter, the performance features of the cascade multi-level inverter with novel partial unit feedback structure is compared carefully; both the novel and traditional inverter have the same regeneration state. The simulation wave form of the power unit in the proposed inverter is shown in Figure 9, and Figure 9 (a) demonstrates the voltage wave form of direct bus bar in non-feedback unit. It can be learned from the figure that the energy back feed and the direct voltage increase quickly when the motor is braking. The modulation wave of H Bridge in the inverter side is adjusted when the voltage is 1800V, and the output voltage is 0, which means the non-feedback unit are bypassed and the energy flow to the middle three energy feedback units. During this process, the voltage is approximately the same, and has little loss. Figure 9(b) shows the voltage waveform of direct bus bar in energy feedback unit, and the scheme of full commutation control of rectifier with direct voltage out race is performed, the voltage of bus bar can stabilize at the set value quickly when its load is in electricity generation state, thus it has excellent dynamic response. The voltage waveform of H Bridge inverter with non-feedback unit and feedback unit are shown in Figure 9(c) and Figure 9(d) respectively. The ordinates in Figure 9 have the same meaning as the former one.



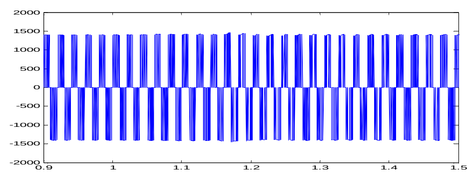
a Not with dc bus voltage feedback unit



b Energy feedback unit dc bus voltage



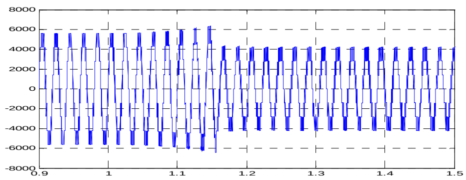
c Do not feedback unit H bridge converter output voltage



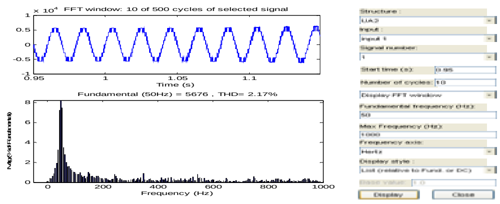
d Energy feedback unit H bridge converter output voltage

Figure 9. Simulation waveforms of new units

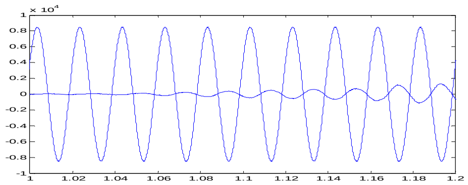
The main simulation waveform of the novel inverter is shown in Figure 10, and Figure 10 (a) is the phase voltage waveform of five power units. It can be learned that the output voltage amplitude is 5 times more than power unit amplitude in motor state, which is 11 electrical level output. Two non-control units are bypassed and only three energy feedback units are working after regeneration braking, and the output voltage is 7 electrical level with three times amplitude that of power unit. Under this circumstance, it is necessary to compensate the output voltage via increase the modulation ration. Figure 10(b) is the analysis of frequency of output phase voltage, and the main distortion ratio of harmonic wave is 2.17%, and the effective voltage value is 4014V, and the line voltage is 6935V, thus the voltage amplitude and harmonic wave content can meet the load of motor. The main output phase voltage, phase electricity waveform (amplified 20 times) and electricity frequency analysis are shown in Figure 10(c) and Figure 10 (d) respectively. It can be learned that the electricity reverse and energy flows from load to grid when motor is in electricity generation state, and the waveform of input current is in fine sine shape, and it is the unit power factor of grid voltage approximately. The main distortion ratio is 1.27%, and the harmonic content is low. The electricity control loop has quick dynamic response and high control accuracy. Figure 10 (e) shows the waveform of motor speed with the proposed inverter.



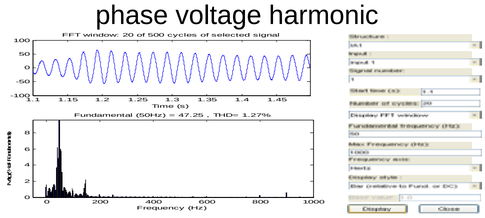
a Five unit total output phase voltage



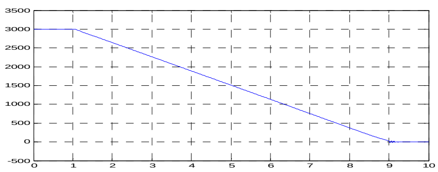
b New type inverter five unit inverter output phase voltage harmonic



c Five unit total feedback voltage, current waveform(current amplification 20 times)



d Five unit total feedback current waveform harmonic



e Motor speed

Figure 10. Simulation waveforms of new cascaded inverter

The simulation results have verified the correctness and feasibility of the topology and control strategy of the proposed partial energy feedback cascade multi-level inverter.

5. Conclusion

Traditional high-power cascade multi-level inverter cannot transmit energy in two-ways, which would limit its application enormously. A novel partial unit energy feedback multi-level inverter is proposed in this paper, which replaces uncontrollable diode Rectifier Bridge in partial units with three phase PWM rectifier. The energy can be transmitted in two-way by frequency converter, and the energy feedback is realized. Meanwhile, in order to gather the energy to the feedback unit, the control policy in inverter side should be modified: checking the direct voltage in non-feedback unit separately, and when it surpasses the set value, and then modulate it to the bypass state. The feasibility of the policy has been verified by the simulations, and the results demonstrates that this topology and control policy can not only feedback regeneration energy efficiently by power factor unit, but also stabilize the voltage of direct current in bus bar effectively and ensure the quality of the output voltage in inverter. Practically, the number of IGBT can be decreased greatly, and reduce the complication of the isolation transformer, and save investment effectively.

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