Multi-Level Converters for Large Capacity Motor Drive

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***Abstract* -- The two-level PWM inverter has expanded in industrial applications because it was able to achieve maintainability and high performance to surpass the DC drive by the development of the vector control and the IGBT (Insulated Gate Bipolar Transistor). However, as the main motor drive of the metal plant rolling mill, the two-level inverter output voltage was too low and capacity was too small, so the DC drive was used for a long time as the main drive.**

The 3-level NPC circuit (Neutral Point Clamped) was introduced as a new circuit which can output two times higher voltage and the two times cleaner waveform than the 2-level circuit.

The improved power devices such as GCT (Gate Commutated Turn-off) Thyristor and IEGT (Injection Enhanced Gate bipolar Transistor) were developed and applied to 3-level inverter after 2000. The switching performance was improved and the efficiency of the inverter was improved to about 99%. Now, most of the new main drives of the metal plant rolling mill are using the 3-level inverters.

There are other large motor drive applications, such as fans, pumps, and compressors. Usually, these motors are directly connected to the commercial power line and flow is changed by the mechanical means, such as dampers and bypass valves, which are inefficient. Recently, our society is becoming more focused on saving energy, and MV inverters, directly operating (without mechanical means) the electric motors in these applications at adjustable speed, are used to save energy.

Recently, LNG (Liquefied Natural Gas) is considered as an important energy source that can be transported from the gas fields to the consumers that need it. The LNG compressors are often very large capacity of 75MW or greater. Initially it was driven by the gas turbine system. Now, it is changing to an all electric motor drive system because of higher efficiency and maintainability. To meet the very large capacity required, a 5-level inverter was developed, with the rating of 7.2kV and 30MVA. It can be applied in parallel up to 4 sets, for a maximum capacity of 120MVA. The 5-level inverter has an excellent performance of high voltage and clean output voltage waveform.

***Index Terms*--3-level inverter, 5-level inverter, AC motor drive, PWM converter, PWM inverter, Variable Speed Drive (VSD) and Voltage Source Inverter (VSI)**

I. INTRODUCTION

Along with the development of the power devices, the AC drive system has improved. Fig.1 shows the progress of the power devices and the drive systems development. The diode and thyristor were developed at first. The thyristor was able to turn on the power, so it was applied in various types of drives such as dc drive, current source inverter, Load Commutated Inverter (LCI) and cycloconverter. But the thyristor cannot turn off by itself, so it must be turned off with the help of outside conditions.

Then GTO appeared with a function of turn on and turn off capability. Then the GCT/IGCT was developed as fast switching device. Now, the GCT/IGCT is used for large ac drives.

And IGBT and IEGT were also developed and now used widely for large ac drives.

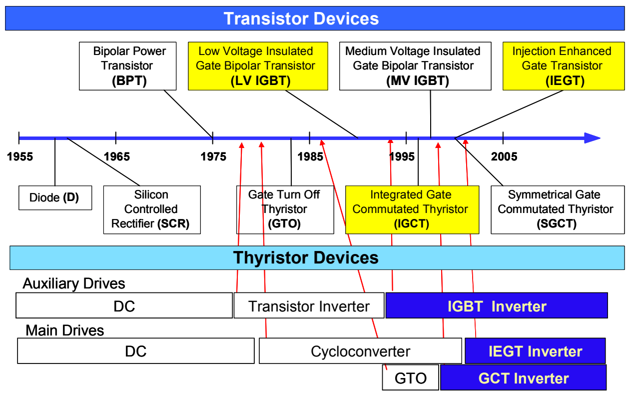


Fig.1 Progress of the power devices and the drive systems

II. THE CURRENT SOURCE INVERTER AND THE VOLTAGE SOURCE INVERTER

Fig.2 shows the circuit of thyristor current source inverter with series connected diode. It was designed to turn off the thyristor with the help of capacitor voltage.

The small and medium motors of fans and pumps were directly connected to the commercial power line and flow was changed by the mechanical means, such as dampers and bypass valves, which are inefficient. The application of the variable speed drive began to drive these motors with current source thyristor inverter. The main reason was to save the electricity bill by operating the motor at variable speed depending on the required flow. There was also a secondary benefit of reducing carbon dioxide emission due reduction of electricity use. But the application was limited because it was necessary to design the inverter and its capacitor specifically to fit the motor parameter.

By the end of 1980s, the IGBT was developed. The IGBT was developed as turn on and off device. It had many features such as, high switching frequency, simple gate circuit and more. So it was applied to voltage source inverter and the IGBT inverter became the most popular AC drive system for the medium to small capacity range. Fig.3 shows the circuit of voltage source IGBT inverter.

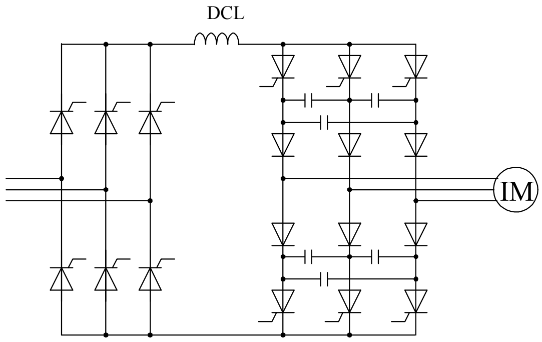


Fig.2 Thyristor current source inverter with series connected diode

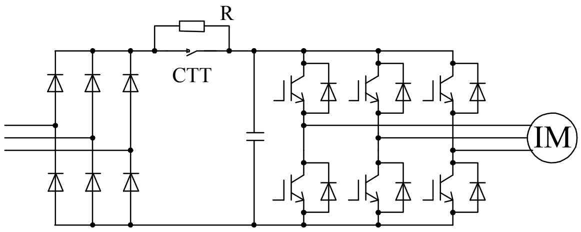


Fig.3 Voltage source IGBT inverter

III. LCI AND CYCLOCONVERTER

LCI and cycloconverter, with thyristor as the main device, were used for large capacity AC drive. Fig.4 shows the circuit of the LCI. LCI consists of converter thyristor bridge and inverter thyristor bridge. LCI realized the high voltage output with series connected thyristors. The inverter thyristor is commutated with the help of motor voltage. At low speed, the inverter thyristor commutate with the help of converter thyristor bridge because the motor voltage is almost zero and can not turn off until the current becomes zero. So the LCI was mainly used for fan, pump, compressors and main stand of wire rod mill which are running continuously. The capacity can be increased by the series connected thyristors and 12 pulse connections to more than 50MW.

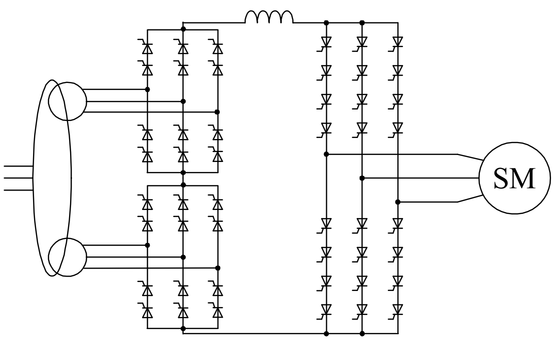
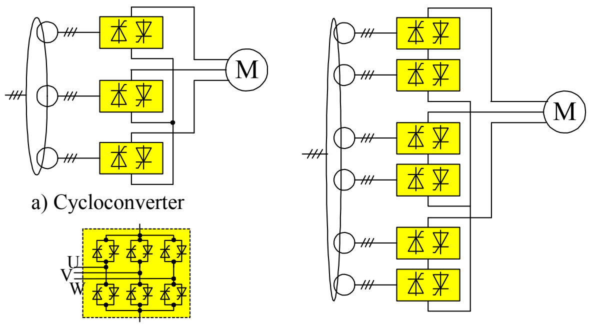


Fig.4 LCI circuit

Fig.5.a) shows the cycloconverter circuit. Cycloconverter consists of three thyristor bridges. The cascade connection was applied to get higher output voltage as Fig.5-c). The cycloconverter had excellent features such as a high performance speed control, easy maintenance and more. It was applied to the rolling mills of steel plant instead of dc drives. But the power factor was low, approx. 0.5 to 0.8, and generated large amount of harmonics. Then power system required power factor correction and harmonics filters. And the top output frequency was limited to approximately 1/3 of the input power frequency.

Fig.6 shows a circulating current cycloconverter. It was developed to realize higher output frequency up to 4/5 of the input power frequency. It was able to control the reactive power by the circulating current but it required large capacitor bank to compensate the reactive power.



b) Thyristor bridge of cycloconverter c) 2S connected cycloconverter

Fig.5 Cycloconverter

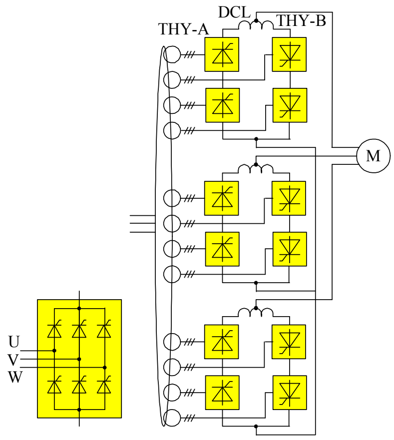


Fig.6 Circulating current cycloconverter

IV. 3-LEVEL INVERTER

Fig.7 shows an inverter using a Neutral Point Clamped (NPC) circuit which is called a 3-level inverter. The 3-level inverter can output two times higher voltage than 2-level inverter. Fig.8 shows three level of switching. Fig.9 shows phase output voltage and line to line voltage. The voltage and current waveform is much cleaner than that of a 2-level inverter without increasing the switching of each device.

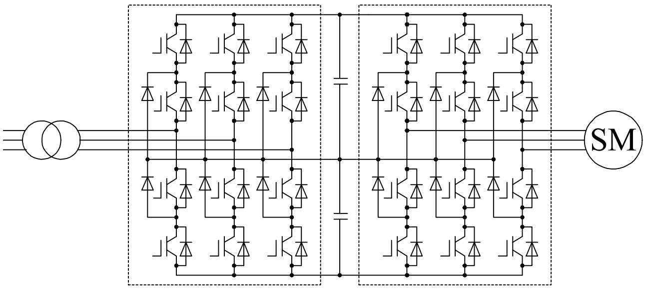
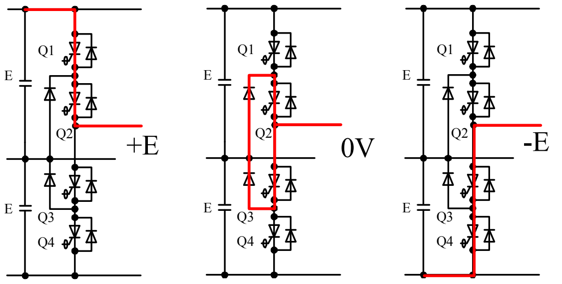


Fig.7 3-level inverter circuit



a) +E output b) 0V output c) –E output

Fig.8 Typical switching waveform of 3-level inverter

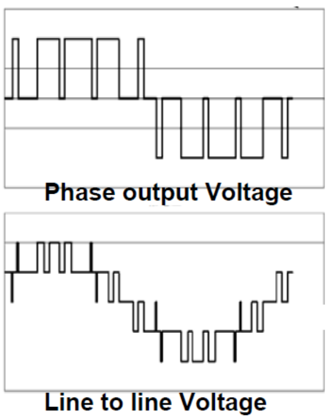


Fig.9 Phase output voltage and line to line voltage of 3-level inverter

A. 3-Level GTO Inverter

GTO was developed in mid. 1980s as shown above. GTO was applied to 2-level inverter like Fig.3 at first. The switching frequency of the GTO was not fast enough and generated large harmonics. Therefore, the application of GTO inverter was limited.

The 3-level GTO inverter was developed in 1990s. The switching waveform was improved and the output voltage became two times of 2-level inverter. Then harmonics was reduced and higher voltage output was realized. At the same time, large GTO rated 6kV-6kA was developed and 3-level GTO inverter of 3.3kV-10MVA was developed with the GTO. The rating was enough to drive the rolling mills of steel plant. But the GTO inverter required complicated snubber circuit and anode reactor to suppress the di/dt and dv/dt.

B. 3-Level GCT/IGCT Inverter

GCT/IGCT is a fast switching type of GTO. Fig.10 shows the GCT device and the gate drive unit of the GCT. It was applied to 3-Level GCT/IGCT Inverter. The rating of the GCT inverter was 3.8kV-12MVA with 150%-60 seconds overload. The efficiency was improved to 98%.

The gate drive circuit is designed to inject large current pulses with high di/dt into the gate terminals. So, the gate terminal of the GCT device is designed to be ring shaped as shown in Fig.10.

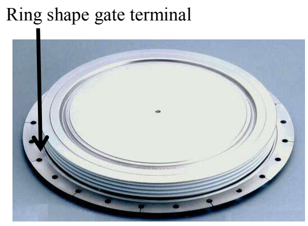


Fig.10 GCT Power Device with Gate Drive Unit models

C. 3-Level IEGT Inverter

The IEGT was developed as a higher voltage rating and larger current rating device of IGBT. The gate control signal is almost the same as that of IGBT. The gate can turn on and turn off the large power with a very small voltage signal. This made the gate control circuit to be much simpler and more reliable. Fig.11 shows a Φ125mm press-packaged IEGT and gate drive board.

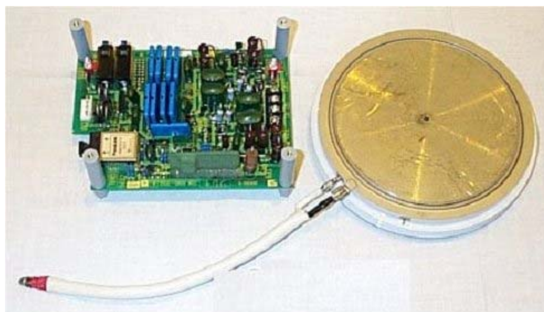


Fig.11 IEGT and Gate Board

The rolling mill is a very heavy-duty application. Very large current flows with impact of metal sheet rolled in, and sometimes it reaches the current limitation. And no load is applied while waiting for the next rolling. So, the temperature of the power device changes very frequently. It becomes a thermal stress. The press pack type device has a higher reliability against thermal fatigue compared with module packaged type devices, because no bonding wires are used in the IEGT package.

Fig.12 shows the over view of IEGT Inverter. The rating is 10MVA with 150%-60 seconds overload. The efficiency was improved to approx. 99% with a help of the fixed pulse pattern control.

Fig.12 10MVA IEGT inverter

D. Parallel Connection

The capacity of the rolling mill in steel plant ranges from several MW to 20 MW and also requires an overload of 175% or 225%. Therefore, inverters are combined to increase the capacity as in Fig.13.

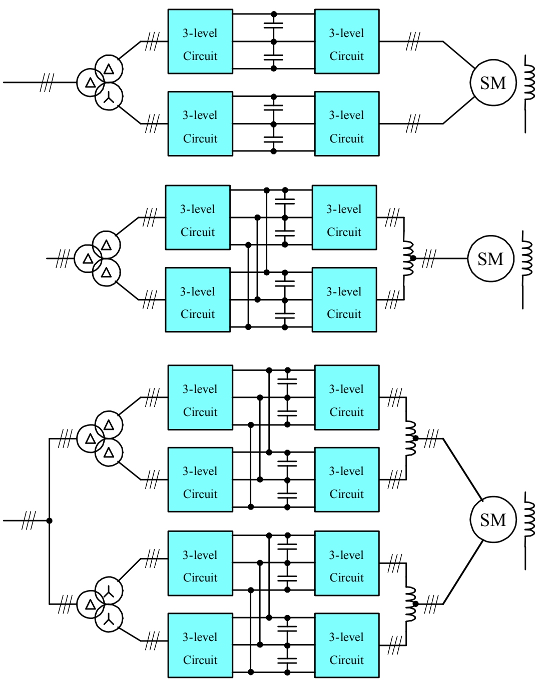


Fig.13 Lineup of large inverters

E. Series Connection

The output voltage of the voltage source inverter can be increased using series connected devices. Fig.14 shows the series connected 3-level inverter. The output voltage can increase twice of the standard 3-level inverter. The voltage balance is one of the important issue and active gate system and/or passive snubber system are applied. The switching frequency is same as standard 3-level inverter. The power device is IGCT, IGBT and IEGT.

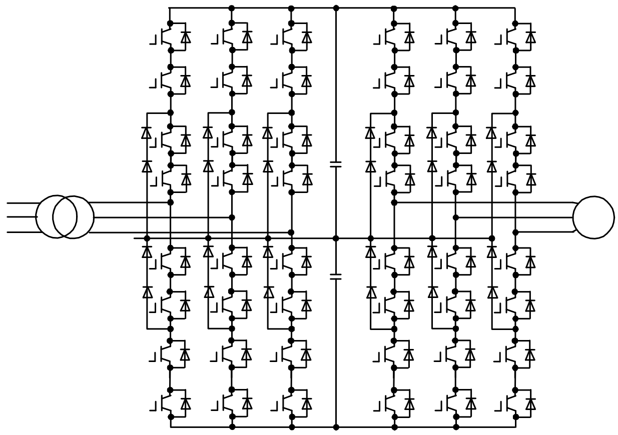


Fig.14 2 in series device type 3-level inverter

V. 5-LEVEL INVERTER

Fig.15 shows a configuration of 5-level inverter. One phase of the 5-level inverter consists of two NPC legs. These phases are combined with a star connection for 3 phase output.

The 5-level inverter can output two times higher voltage than the 3-level inverter. The separation insulation is mutually done with the input isolation transformer so that DC voltage of each phase cannot be the same potential voltage to each other.

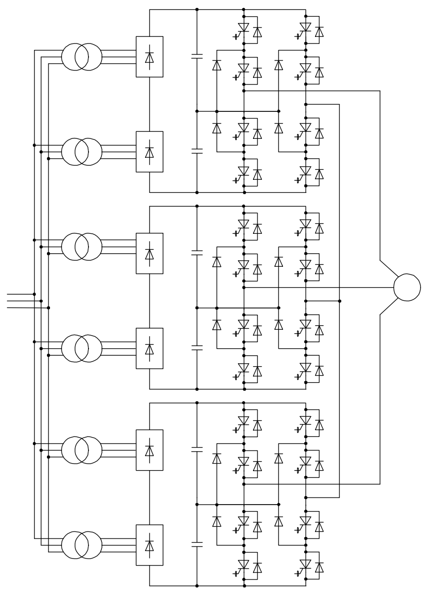


Fig.15 5-level inverter circuit

It was developed to apply to very large motor of 5MW to 100MW. Fig.16 shows 5-level GCT Inverter. Table 1 shows the specification of 5-level GCT Inverter.

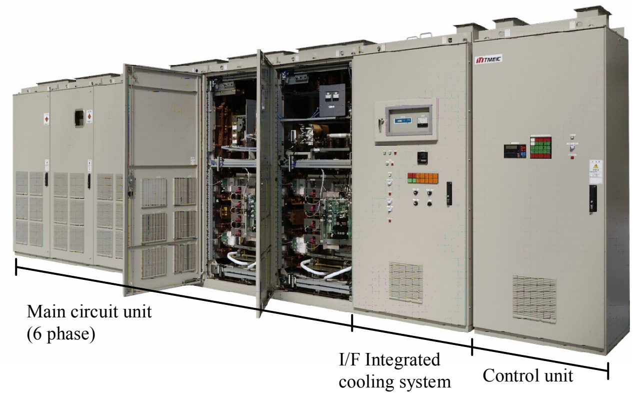


Fig.16 5-level GCT inverter

Fig.17 shows the waveform of 5-level inverter. Fig.17a) and (b) shows the voltage output of the UA and UB bridge of U phase. The U and V phase output voltage is 5 level as Fig.17(c) and (d). Then the line to line voltage is 9 level as Fig.17(e). The output waveform of 5-level inverter is much closer to sinusoidal and higher output voltages than that of 3-level inverter. So, the torque ripple is very small. It meets the requirements of the LNG compressor and more applications.

TABLE 1
SPECIFICATION OF 5-LEVEL GCT INVERTER

Names and items	Specification
Principle of main circuit technology	5-level GCT VSI
Capacity	30[MVA]
AC output voltage	7200[Vrms]
AC output current	2400[Arms] (overload 110% per minute)
System structure	Multi-bank: Max. 4 banks in parallel Maximum output 120MVA
Rectifier circuit	12 phase diode converter×3set =36 phase
Cooling system	De-ionized water cooling
Redundant system	Available as option

Fig.18 shows the test result of the inverter output voltage and current waveforms at rated operation speed.

Fig.19 shows the configuration of a 7.2kV-120MVA system. It consists of 4 banks of 5-level GCT Inverter. These inverters are connected in parallel using balancing reactors. Typically, LNG plant requires redundant configuration. This system can operate with 3 banks in case of one bank failure. Also, the redundant controller can be applied to extend the availability.

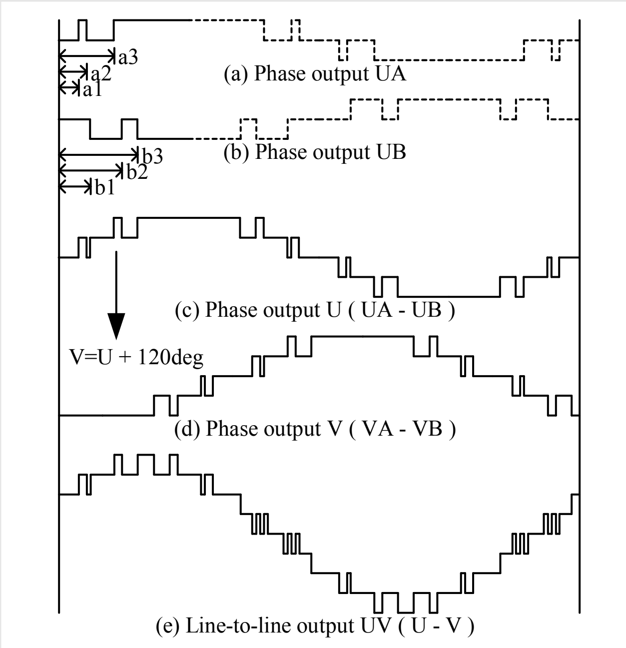


Fig.17 Output voltages of 5-level inverter

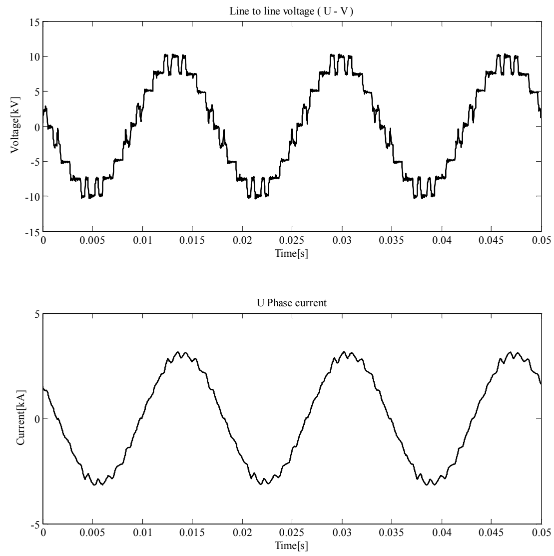


Fig.18 Inverter output voltage and current

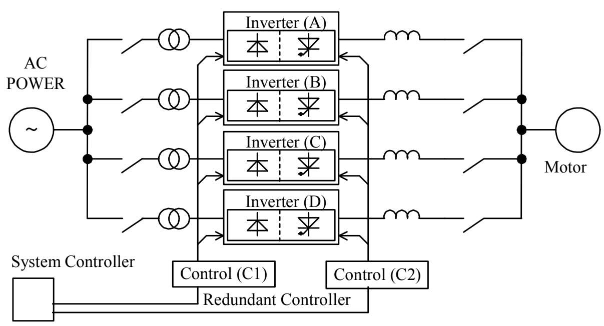


Fig.19 Configuration of 120MVA inverter

VI. MV INVERTER

Fig.20 shows Series Connected H Bridge 2-level (SC-HB 2L) inverter. Six single-phase cell inverters arranged in series are connected in three-phase star connection to output a high voltage without using a step-up transformer.

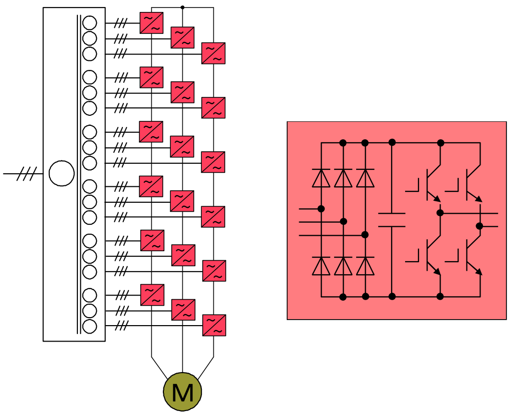


Fig.20 Configuration of 6.6kV SC-HB 2L inverter

Fig.21 shows the outline of a 6.6kV SC-HB 2L inverter. The panel consists of transformer panel, converter panel and automatic control panel. So the installation is simple. The phase output voltage is 13-level.

Fig. 22 shows the line to line output voltage waveform of the inverter. The line to line voltage is 25 level and almost sinusoidal. This output voltage has less micro-surge influence on Motor winding isolation, and it is helpful to apply on an existing Motor that is not designed for inverter drive.

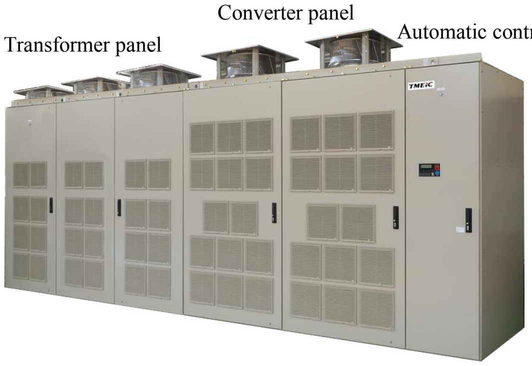


Fig.21 Outline of a 6.6kV SC-HB 2L inverter.

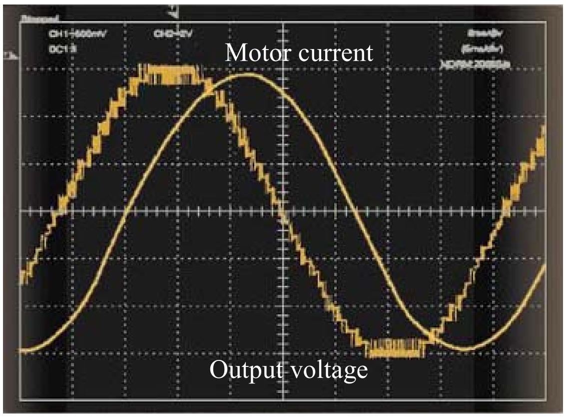


Fig.22 Output waveform of 6kV SC-HB 2Ll inverter

Fig.23 shows the line up of SC-HB 2L inverter. The SC-HB 2L inverter can change the output voltage by the number of the cells series connected.

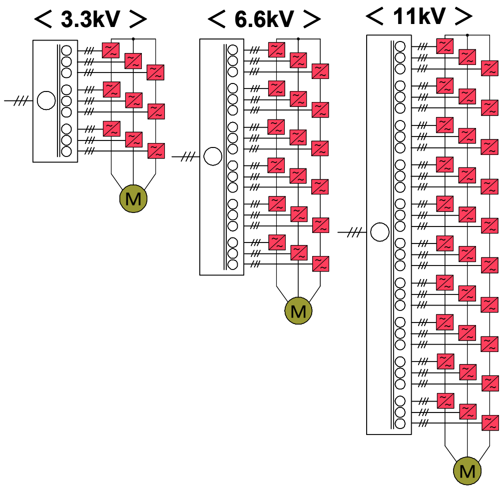


Fig.23 Line up of SC-HB 2L inverter

Fig.24 shows the configuration of 11kV-20MVA system. It consists of 2 banks of 11kV-10MVA SC-HB 2L Inverter. These inverters are connected parallel using balancing reactors.

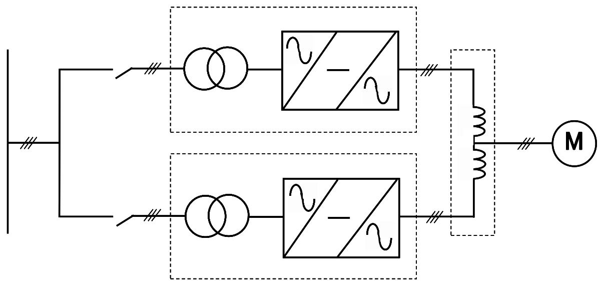


Fig.24 Configuration of 20MVA SC-HB 2L inverter

VII. Conclusion

Based on the development of the power device and main circuit design, the multi-level inverters are developed and applied to the large drive market in wide range of industries. Especially the improvement of voltage source inverter has been significant and reached the capacity range up to 120MVA.

The multi-level inverter contributes to energy saving, and wider use can also contribute to reduce the CO_2 emissions.

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