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STUDY OF LARGE VSI DRIVE SYSTEM FOR OIL AND GAS INDUSTRY

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ABSTRACT

Reduction of energy consumption and CO_2 emissions are recognized as important issues in today's world. In addition, oil and gas companies are looking for ways to increase their capacity and maximize system uptime in order to meet the global energy demand. To realize these goals, oil and gas facilities are looking for

electrical solutions as prime movers on their compressor trains. These solutions make use of large scale variable speed drive (VSD) systems such as the voltage source inverter (VSI) with high power alternating current (AC) motor drive systems. The VSI is more widely used to match the motor speed and torque to the optimum load requirement, thereby saving significant electrical cost. Since large electrical drive systems are a relatively new technology with limited field data, the full load test of 30 MVA five-level VSI system was carried out on a test stand to measure critical data necessary to evaluate system performances.

INTRODUCTION

In recent days, power semiconductor devices have moved toward higher voltage, greater continuous current, faster switching speed, easier switching with high efficiencies and lower losses. Especially in the field of oil and gas, the large AC motor drive system has been used in many industries for helping energy savings with its high efficiency. The gas turbine has been the conventional power source of large capacity compressors, such as those applied to liquefied natural gas (LNG) refrigeration trains. With today's existing and proven technologies, it is possible to use a large capacity VSI system for this application. This solution will provide significant economic and environmental gains to the operator.

The VSI is widely used to match the motor speed and torque to the optimum load requirement, thereby saving significant electrical cost. VSI systems are used throughout industry in a variety of applications. They are available in fractional power ratings and the 30 MVA VSI drive system discussed in this paper can be used in parallel to achieve very high motor power levels, up to 115 MW.

As a VSI is a type of electronic motor control system that is used to control the motor speed and torque, the VSI can also be used as a "soft start" to reduce the strain of startup transients on the electrical and mechanical system. This is in fact a very common practice today.

Recently Toshiba Mitsubishi-Electric Industrial Systems Co. (TMEIC), has developed a five-level gate commutated turn-off thyristor (GCT) VSI AC motor drive system, which is the world's largest capacity AC drive usable by the oil and gas industry.

The five-level main circuit unit has neutral point clamped (NPC) legs configured with two legs per phase in a single phase star connection. The five-level configuration raises the output voltage by a factor of 2 compared to the three-level main circuit using the same device. Minimization of the anode reactor is possible by using a gate commutated turn-off thyristor that connects to develop an NPC main circuit unit with high current and low losses. The resulting device was a main VSI power bank rated 7.2 kV-30 MVA. Up to four of these VSI power banks can be connected in parallel for a combined power rating of 120 MVA (approximately 115 MW).

The authors built a 25 MW motor drive system and evaluated the system by a back-to-back test. (TMEIC has developed a five-level GCT inverter of 30 MVA drive system to do back-to-back tests. The test has been performed to confirm the total system performance at a motor factory ended on December 2008. Some test results are presented in this study.) In this study, the authors applied the 7.2 kV 30 MVA VSI bank to a 25 MW synchronous motor (SM). To load the SM, a synchronous generator (SG) is driven by four three-level injection enhanced insulated gate bipolar transistor (IEGT) inverter banks each with a regenerative pulse width modulated (PWM) converter and PWM inverter. This IEGT inverter is a type of VSI commonly found in steel mills.

PRINCIPLE OF THREE-LEVEL INVERTER AND FIVE-LEVEL INVERTER

In Figure 1(a), the normal Gretz connection inverter is called a two-level inverter in the sense of two output levels (+E and −E) of phase voltages. In Figure 1(b), an inverter using an NPC configuration is called a three-level inverter. In the three-level inverter, output voltage and current are much more sinusoidal and the total harmonic distortion (THD) is better when comparing to that of a two-level inverter. In the three-level inverter, the efficiency at full load is higher than the efficiency of a two-level inverter. Higher efficiencies at rated power also reduce the size of the cooling system and improve the system reliability. Efficiency of the three-level inverter at reduced power is also improved (Ikonen, et al., 2005).

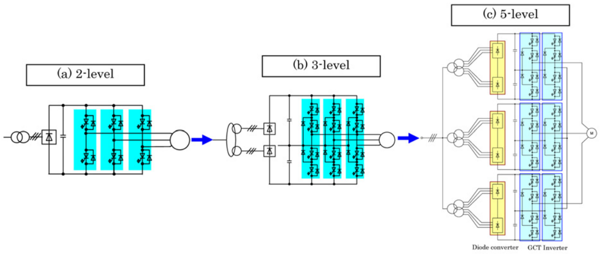


Figure 1. Development of Main Circuit Technology.

In Figure 1(c), a five-level inverter is configured with two NPC legs per phase, connected in a single phase. These phases are combined with a star connection for three phase output.

The separation insulation is mutually done with the drive isolation transformer and the diode rectifier so that direct current (DC) voltage of each phase cannot be the same potential voltage to each other. The diode rectifier portion is placed in each of the 12 phases of the rectifier. A comparison of two-, three-, and five-level circuits is shown in Table 1.

Table 1. Comparison of Two-Level, Three-Level and Five-Level Circuits.

	(a) 2-level	(b) 3-level	(c) 5-level
Phase Voltage	+1E, -1E	+1E, 0, -1E	+2E, +1E, 0, -1E, -2E
Line Voltage	+1E, 0, -1E	+2E, +1E, 0, -1E, -2E	+4E, +3E, +2E, +1E 0, -1E, -2E, -3E, -4E
THD	Larger		Smaller
Losses	Larger		Smaller

Two-level and three-level VSI are commonly used in industrial plants. In general, the series connection needed for high voltage applications is difficult for the voltage based semiconductor devices used for VSI. For this reason, the current source inverter such as the load commutated inverter (LCI) has been often used for high voltage applications. Unfortunately, the current source configuration has many drawbacks that the designer must consider.

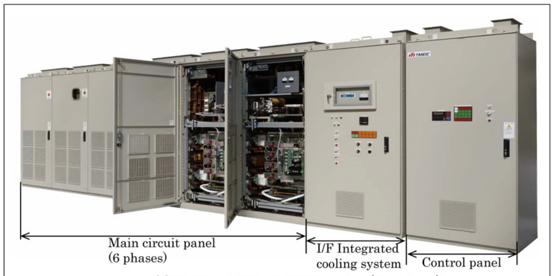
The five-level inverter brings an improvement to the VSI. Comparing to a three-level inverter, output voltage and current of the five-level GCT is much more sinusoidal and the THD is lower. Higher output voltages are achieved. Thus, the application of VSI is expected to spread for higher voltages by using five-level technology.

ILLUSTRATION OF FIVE-LEVEL GCT VSI SYSTEM

The five-level GCT VSI system is configured with three pairs of single phase three-level GCT inverters that operate as a three-phase five-level inverter. The main circuit unit and main circuit board can be commoditized with other drive systems.

The system has been developed into a 30 MVA inverter that produces 7.2 kV output voltage. As the capacity of a one bank five-level GCT inverter is 30 MVA, it is possible to obtain 120 MVA by connecting four banks together. Applied to a compressor, it is not necessary for the variable frequency drive (VFD) to have the ability of power regeneration. Therefore, a diode converter circuit is introduced to attain a smaller footprint and lower cost.

Figure 2 shows the structure of prototype five-level GCT inverter and the specification of the inverter is mentioned in Table 2. Figure 2(b) shows the circuit configuration of the main power block in a five-level GCT inverter. It is developed with main switching devices such as GCTs (GC1 to GC4) and freewheel diodes (DF1 to DF4) connected in parallel and coupling diodes (DC1 and DC2) as shown in Figure 3.



(a) Outline of 5-level GCT inverter (Prototype)

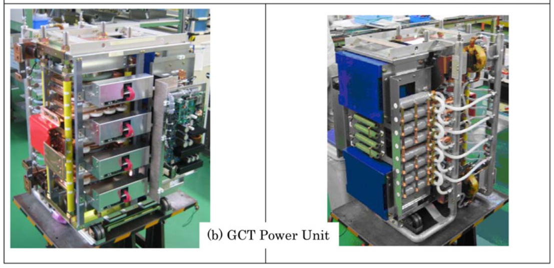

(b) GCT Power Unit

Figure 2. (a) Outline of Five-Level GCT Inverter (Prototype), (b) GCT Power Unit.

Table 2. Specification of Five-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	Maximum 4 banks in parallel for multi bank structure Maximum output 120MVA
Rectifier circuit	12 phase diode converter×3set =36 phase
Cooling system	De-ionized water cooling
Development motivation	Large capacity and high output High-density mounting

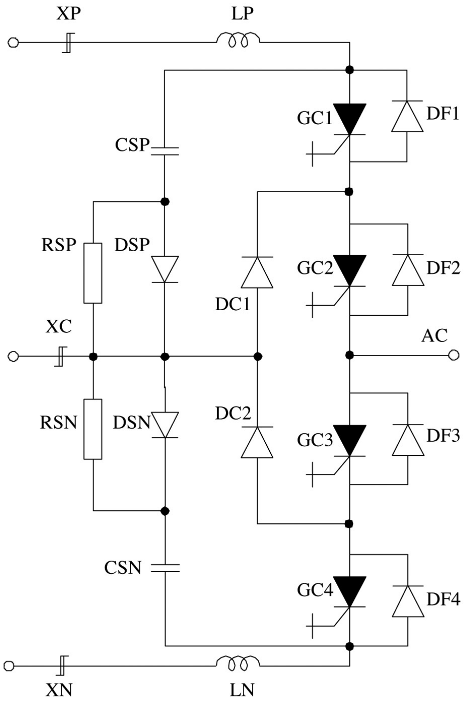


Figure 3. Schematic Diagram of Main Circuit Unit of Five-Level GCT Inverter.

A snubber circuit (configured with CSP, CSN, RSP, RSN, DSP, DSN devices) is connected for the overvoltage control when any device is intercepted. The changes of current (di/dt) are controlled by anode reactors (LP, LN) to decrease the strain of recovery of the diodes. A saturable core is introduced to minimize this capacity, which mainly controls this change of current on the time of transition. In the stationary state, current passes through a smaller anode reactor. Thus, it is possible to decrease the power losses of the clamp snubber circuit so high efficiencies with a compact device can be designed (Yoshizawa, et al., 2008).

GCT (Gate Commutated Turn-off Thyristor) Power Device

Figure 4 shows the GCT power device used in this study. The gate terminal of the GCT device is ring shaped. The gate drive circuit must inject large current pulses with high di/dt into the gate terminals. However, it was not possible to make a ring shape in the traditional gate drive unit (GDU) due to the system structure (the turn-off circuit must be nearer to the ring gate terminal). Compared to the traditional GDU design, the newly developed GDU has a shape that matches the ring shape of the gate terminal. Gruening and Koyanagi (2004) found that the new GCT and GDU have improved switching characteristics compared to earlier devices. And this newly developed GDU model is designed by the authors' company, which helps to build a compact gate drive.

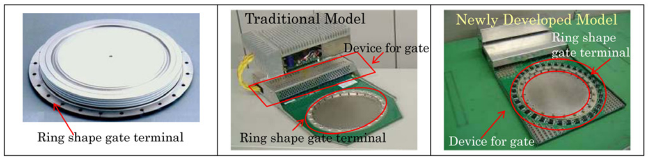


Figure 4. GCT Power Device with GDU Models.

ARCHITECTURE OF THE TEST SYSTEM

The 30 MVA test is essential for evaluating system performance of a five-level inverter drive system. It is necessary for the generator and regenerative inverters to be fully rated for the full load back-to-back test. Thus the authors developed a 25 MW inverter and synchronous motor (SM) specifically for this test stand. A regenerative load inverter of the type used for an industrial plant was applied as a load system. The load inverter uses the injection enhanced insulated gate bipolar transistor for its main semiconductor switch, and 8 MVA is obtained from each unit (Ichikawa, et al., 2004).

Figure 5 shows a photograph of the experimental setup for system performance and evaluation. It is possible to operate four load IEGT inverter banks in parallel to produce 32 MVA and regenerate 25 MW of power. To match with the rated inverter, a 25 MW synchronous generator was developed. The SM and SG are developed two poles (2P) and four poles (4P), respectively. A variable speed gear with a 2:1 ratio is connected between the SM and SG to match the speeds. The drive isolation transformers are connected with the inverters so that the input voltage matches the 11 kV main power grid. The power will be circulated by this operation between the SM and SG (Tsukakoshi, et al., 2005).

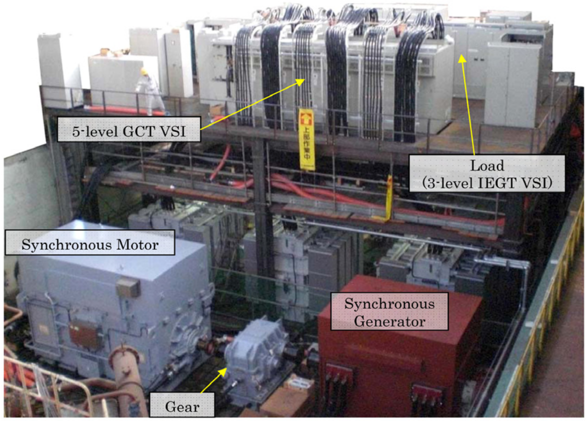


Figure 5. Test Setup for System Performance.

Figure 6 shows the schematic diagram of the test system used in this study. The output of the 30 MVA VSI powers a two-pole, 25 MW motor that is connected to a four-pole generator through a gearbox. Five-level GCT VSI helps to control the speed, which is connected to the SM. Torque and voltage control is done with the three-level IEGT VSI. The electrical power taken from the generator passes through four parallel, regenerative, VSI units to be put back into the power system. This will reduce the power requirements for the full 30 MVA test to supplying only the make up power from the electrical losses.

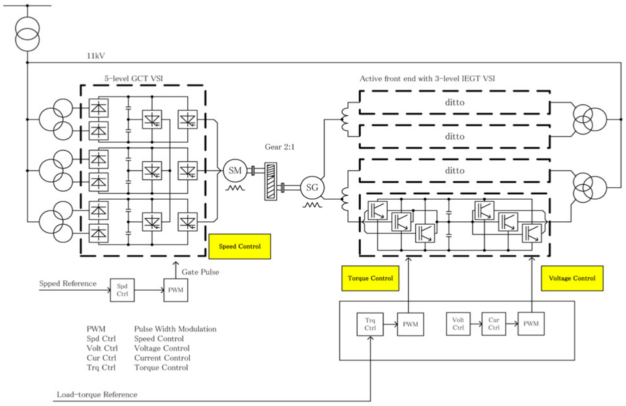


Figure 6. A Schematic Diagram of 30 MVA VSI Test System.

The drive isolation transformers, motor and generator have been designed and built specifically for this test stand. The test stand closely models actual field operation of the motor on a compressor train. The VSI supplies full rated voltage and current to the motor.

This test system allows the measurement of important data such as VSI input and output waveforms. Measurement of the VSI harmonics will be useful for system analysis and simulations for applications such as compressor trains.

Figure 7 shows a photograph and circuit diagram of the actual 30 MVA VSI (prototype) used in this study. The VSI has a capacity of 30 MVA at 7.2 kV output voltage. The input section of the VSI is a 36-pulse diode rectifier. The output section of the VSI, powering the motor, is a five-level voltage source inverter with GCT thyristors. The inverter uses the high powered GCT semiconductor switches to create a PWM type sinusoidal curve to the motor.

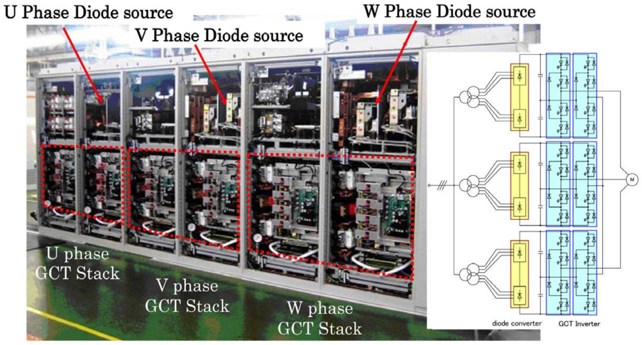


Figure 7. A 30 MVA Drive System (Prototype) and its Circuit Diagram.

One of the benefits of the five-level inverter topology and sophisticated PWM topology is that it produces very little torque ripple. This is very important for high powered compressor applications.

RESULTS AND EVALUATION

Figures 8 through 11 show the result of inverter output voltage of the five-level circuit that is changed according to the variation of speed. It demonstrates a comparatively clean voltage output waveform while operated at full speed (100 percent).

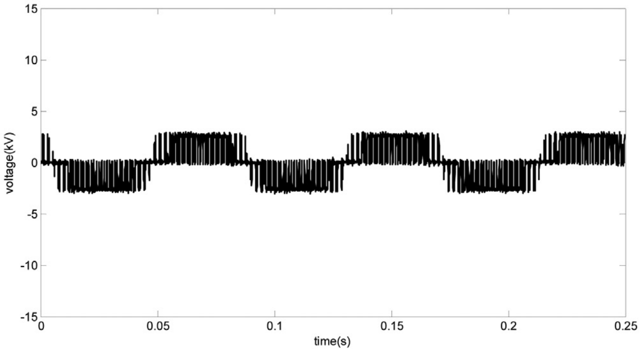


Figure 8. Line-to-Line Voltage at 20 Percent Speed.

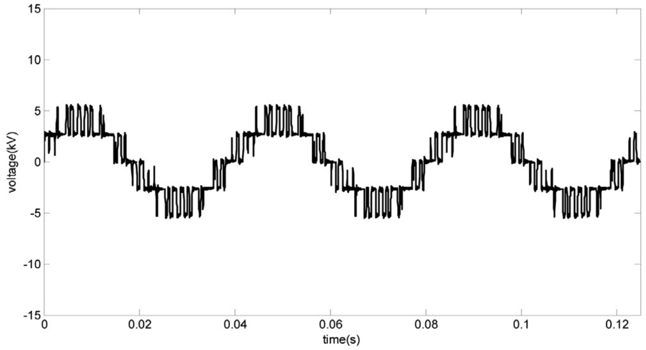


Figure 9. Line-to-Line Voltage at 40 Percent Speed.

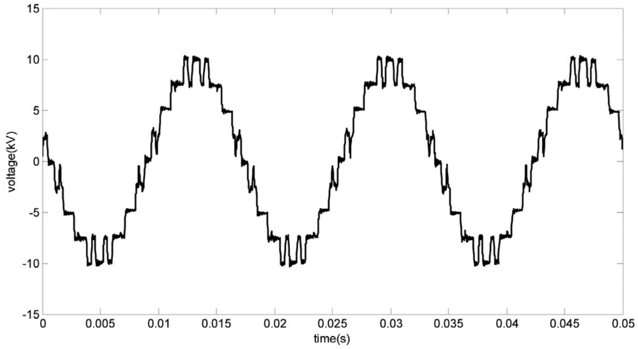


Figure 10. Line-to-Line Voltage at 100 Percent Speed.

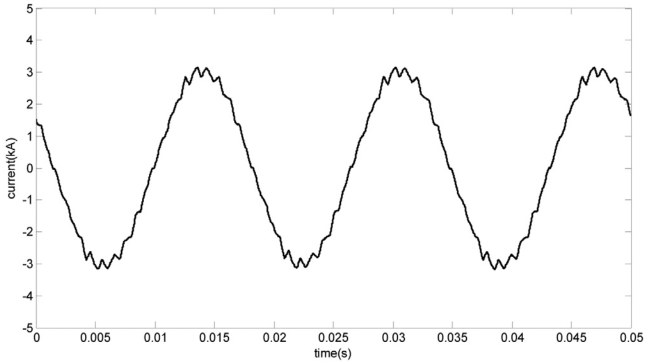


Figure 11. U-Phase Current at 100 Percent Speed.

Figure 8 shows the result of line-to-line voltage at 20 percent speed. It has three-levels (positive, zero and negative) of output voltage. Though it is mentioned in Table 1(c) that the five-level inverter produces nine steps (+4E, +3E, +2E, +1E, 0, −1E, −2E, −3E, −4E) of output voltage, they are the maximum steps of voltage that can be obtained from the five-level inverter. The voltage increment of inverter is proportional to the rotating speed.

In other words, the inverter operates at low voltage when the speed is low. So, the authors obtained three steps (+1E, 0, −1E) of output for lower voltage shown in Figure 8.

Figure 9 shows the result of line-to-line voltage at 40 percent speed. In this case, it produces five steps (+2E, +1E, 0, −1E, −2E) of output voltage.

Figures 10 and 11 show the result of line-to-line voltage and U-phase current at 100 percent speed, respectively. The output voltage goes to maximum at its full speed. In this case, the authors obtained nine steps (+4E, +3E, +2E, +1E, 0, −1E, −2E, −3E, −4E) of output voltage, which satisfies the concept of line-to-line voltage output of the five-level inverter given in Table 1(c).

In general, it is possible to obtain clean output current when the steps of the output voltage go higher in number. Figure 11 shows the U-phase current at 100 percent speed, which is near to sinusoidal curve obtained in this study.

Though the test was done with the motor connection in this study, the compressor will be connected in the real case and it is necessary to match with the axis of each other. Otherwise high torque ripples occur that cause some damage to the mechanical parts. However, the stress to load systems like shaft or compressor is very small in this study, which helps to avoid breaking mechanical parts.

CONCLUSION

The results of these tests demonstrate the suitability of electric VSI systems for large compressor applications. Therefore, end users may realize the great financial benefits from an all electric VSI drive system as the prime mover on a large compressor train.

It is also possible to obtain clean output, which has a great contribution for compressors in the oil and gas industry. As it is comparatively difficult to apply such a large system in those fields directly, it is necessary to evaluate the whole system by experiment before implementation. In this study, the authors achieved satisfactory results from the tests, which are expected to connect for a better solution for the environmental problems in the near future.

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