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Energy Saving in DC/AC Drive Compressors & Pumps using ZCTF PWM Inverter: A Study

Saeed Jahdi *Graduate Member IEEE, IAENG*, Loi Lei Lai *Fellow IET, Fellow IEEE*

Abstract— **Despite past technologies which were using Steam turbine or Gas turbines to drive industrial compressors, Today, most compressors used in refrigeration and gas compression purposes are using Induction motors with PWM (Pulse Width Modulation) Inverters as a drive or DC motors in heavy industrial loads with DC/DC converters installed. This is due to the fact that these technologies help us to deduct energy consumption and CO_2 emissions which are known as important environmental issues in today's world. As a brief, one of the main advantages gained by the use of these is the fact that the compressors can supply just the exact amount of cooling required. Supplying cooling at a higher level will be avoided and energy will be saved automatically.**

In this paper we will introduce new application of Soft switching PWM converters in compressors with DC drives, presenting a study on how using VSD drive technology or DC-based drive to save energy in compressor and pumping applications. Affects of usages of PWM Inverters/DC-DC converters on lubrication; cooling and parallel compressors usages will be discussed. In this type of DC converters, ZCT or ZVT switching condition is achieved for the switches while the control circuit still remains PWM to act as a DC drive. The proposed AC inverters / DC Converters analysed. Simulation results are presented which confirm the theoretical analysis.

Index Terms— **Compressors, Energy Saving, Variable Speed Drives, Zero Current Switching, PWM drives**

I. Introduction

TODAY, compressors are among most usable tools within any industrial producer. There is an old history behind the improvements of compressors and there are various technologies to design an efficient compressor to compress whether the gas or the liquid in a more suitable condition. There have been eras that engineers tried to design better compressors for the industry but most of them were drived within steam power or mechanical turbines. Now, the greatest modern improvements have happened in the drive technologies that are suppose to initially drive the compressor to run. Comparisons between electrical and mechanical drives show that the electric drives are more competitive and offer better advantages against past gas turbine compressor drives. The main advantages are the lower capital cost, having higher efficiency, a higher availability in applications and lower maintenance costs. Because of their simplicity, electric drives are much easier to operate, control and demand less service and maintenances in application procedures. Therefore, they are even better developed for remote control and operations in industry. The start up procedures is easier than turbine drives and so electric drives are more flexible to operate. Most industrial compressors are using the 3 phase drives (Induction squirrel cage or synchronous), or in some cases there is still preference of using the DC motors as a drive Because of their nature that supplies compressor with a higher initiate traction/pressure. There are various technological aspects of solutions that could distinguish and characterise modern electric-drived compressors, however it has been said that variable speed compressors, which are mostly driven by PWM inverter, are still among the most interesting category. Furthermore, DC/DC converters are used as new method to control DC motors speed due to changes in voltage level and control rotation speed. [1]

In this paper we will have a survey on how VSD Drives can decrease the energy consumption of the compressor and then introduce a new less power-loss type of PWM converter technology; used to supply the heavy industrial DC motor with a proper level of voltage to control motor's speed. After discussing the problems of past PWM inverters and studying today's VSD drives, a new DC converter is provided for DC compressors which includes a simple auxiliary circuit. In addition, for the resonance inductor, the converter uses the transformer leakage and hence does not need any external inductor. The provided converter is analyzed and simulated, and considerations are discussed. The most important advantage of these drives, which will be discussed further throughout this paper, is the ability of a significant energy saving. The paper presents a survey on how and why this technology help us to save energy, how it will reduce energy consumption and carbon emission and why our industrial heavy sectors should try to use it as a base drive platform for industrial DC compressors.

II. Compressors Drives

Compressors are like pumps in behaviour: both increase the pressure and can transport the fluid through a pipeline. Since gases are compressible, the compressor decreases the volume of the gas in the pipe. Liquids in contrast are incompressible, although in some exceptional cases can be compressed, so the important action of a compressor is to

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Saeed Jahdi was MSc Student in Power systems and Energy Management in City University London 2010-2012.

Loi Lei Lai is Professor of Department of Electrical Engineering, Power Systems in City University London, EC1V 0HB, UK.

pressurize and hence move liquids in pipes. There are different types of compressors in technology of compressing gases through pipelines or within a sector, but all have similarities in needs of a drive to operate. [2]

Most of the current AC compressors use VSD's instead of Mechanical turbines to run and so the usages of Electrical Variable Speed Drives are wide spreading day to day in order to help industries to save energy as much as possible. Consequently DC compressors and pumps are used in heavy industrial applications due to their greater initial traction. Both models of compressors drives use a special drive to control and keep the speed (rpm) of the device at a required level, in order to save energy as compared to a fixed-speed equivalent compressor. The most widely used form of Variable Speed Drive technology in the air-Compressing (Compressible gases) Technology is a variable-frequency drive, which converts the incoming Alternative Current power to Direct Current and then back to a new quasi sinusoidal Alternative Current power using an inverter switching circuit to reach a proper frequency and relatively speed. In this paper we introduce application of a PWM converter to use in DC compressors drive which is called Zero current transition Forward converter. The advantages of this new technology are a reduced power cost, reduced power surges and losses (in starting DC motors), and providing a more constant pressure. The disadvantages of the technology are the heavy expenses related to the drive, and the sensitivity of those drives - significantly to heat increase and moisture affects. These topics will be discussed in more details in the next stages of our discussion. Large electrical expense savings can be gained through installing a VSD compressor for AC Drives or a DC-DC Converter for DC drives. Nowadays, most energy producing companies are pressing the industries towards these technologies in hopes of decreasing wasted energy.

III. Variable Speed Drive Technology – AC Compressors Drives

Variable speed drives (VSD) describe equipments used to control the speed of machinery like AC compressors' drives. Where process conditions need adjustment of liquid flow from a compressor, changing the speed of the motor-drive could save energy compared to other techniques for refrigeration gas flow control. In usual conventional AC electric motors which are used to drive the compressors, the motor runs at speeds closely determined by the number of poles and frequency of AC supply (50 or 60 Hz); in contrast with past steam engine drives which had a better variety in speed levels. In this case the numbers of various speeds available is therefore limited by the reason of providing multiple sets of drive windings. In case many different levels of speed or variable speeds are required, other techniques are will be used. [3] Because of the growing awareness of environmental concerns in whole world, better electric power efficiency is essential. Most of the electric energy consumed is passing through electric machines especially higher power MV electric motors. Usual MV induction motor drive systems, like those used for fans, compressors and pumps are directly connected to the power grid source and so are driven at constant speeds (or speeds varying with load level) .[1]

This produces a valuable energy loss for AC drive systems and thus, there is a growing need for a MV Variable Speed motor drive system with significant energy saving capabilities. This is possible with using Variable Frequency Drives. Through industry preference for VFD developments in adjustable speed drives and/or servo-drive applications, the Variable Frequency Drive technology has developed from lower power, lower voltage applications to higher power, MV drives using new power electronic inverter/converter methods. [3] The industry in general and the compressing industry in particular now relying on MW VFDs that consume a huge amount of energy. With Significant rise in demand for MV, high power inverter drives have increased the ability of available semiconductor designs. Readily available semiconductor devices cannot go along with today's required kV and MW ratings. By simply connecting these devices in parallel or series, we can overcome this, but in addition of new current sharing and hence voltage spike problems. This has led our study to developments in multilevel inverter with topologies that semiconductor devices used in very spectacular ways, so the voltage between the inverter parts will be kept low, but the operating voltage and so inverter power will still raise. [2]

It could be said that there are three general categories of electric drives: DC motor drives, eddy current drives and AC motor drives. In domestic compressors; speed drives are categorized as AC motor drives since most these compressors are using induction squirrel cage motors as a drive to run the refrigeration compressors. In Industrial compressors both AC and Dc drives could be used and this is due to the nature of the application. A VSD drive mostly uses less energy than an alternative conventional fixed speed set of operation. On the other hand, since Compressors and pumps are among the most popular energy saving applications in industry these motor mostly being used to drive them. It's because when a compressor is driven by a conventional speed motor, the refrigeration gas flow may occasionally be over than it what's needed to be and makes it colder than needed. Gas flow can be regulated by using dampers to limit the gas flow, but it is more efficient to modify it by modifying speed of the motor dive that runs it.

The first PWM inverter used in VSD application for AC drives had a few serious problems that made it unsuitable for using in VSD application. The main problem of conventional PWM Inverter control is the huge amount of harmonics they produce, causing an unbalanced amount of input current into the motor and consequently vibrations of motor and thermal energy losses. In order to reduce these harmonics there are designs for a low pass filter so that high level harmonics will be omitted, but still these Harmonics can be cause of extended losses and temperature up rise of all elements in the supply procedure (like rotating motors& generators, all transformers, transmission cables and capacitors banks). As a general statement harmonics are main reason for rise in motor losses and the odd harmonics specially 5th, 11th, and 17th harmonics, although they present in very low amplitudes, will reduce the starting torque of machine. The internal temperature rise is mostly due to the harmonics rise that leads to a significant increase in iron and copper power losses and, so, the total losses will increase. Note that main control methods have been addressed in new PWM VSDs to lower harmonics effects particularly on the compressor application motor. Current harmonics in the PWM VSD input stage can be feed back into the power grid network, and may disrupt other equipments feeding in these premises. In Figure 1, a past PWM Inverter that was used to drive an Induction motor is shown, and in Figure 2 shows the harmonics and instability of the load current is visible. Today there are various different ways to reduce these harmonics in a VSD drive application designed to operate a compressor, all based on Power Electronic evolutions. These include Using 6-pulse, 12-pulse, 18-pulse or 24-pulse rectifiers method or using an active IGBT rectifier. The losses and harmonic problems get important mostly in especially in industrial heavy loads. So rather than essential needs for traction in heavy loads, need for reducing energy losses become so important and for this reason technique of using a ZCT PWM converter for DC compressors is used. [4] DC compressors have different application than ACs. In AC drive compressors connect directly to supply or in industrial cases through a PWM-VSI drive, but DC drives have special suppliers and will only used if we need a high traction in heavy industrial loads, Hence they have special consideration like leakage losses.

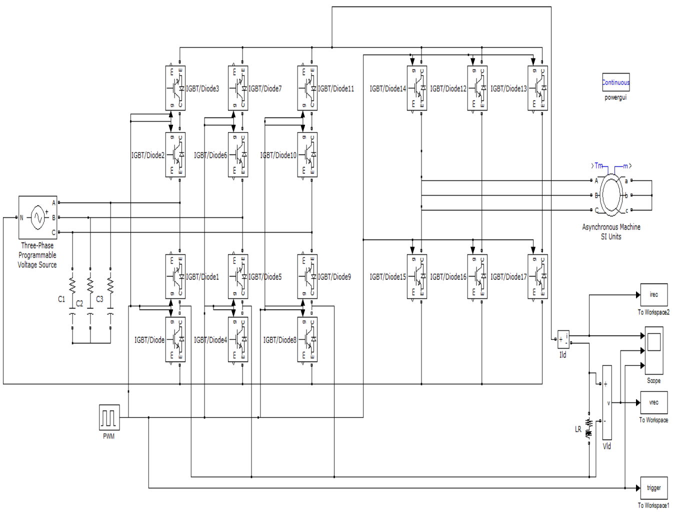

Fig 1. A PWM Inverter inserting current harmonics to VSD AC compressor Drive

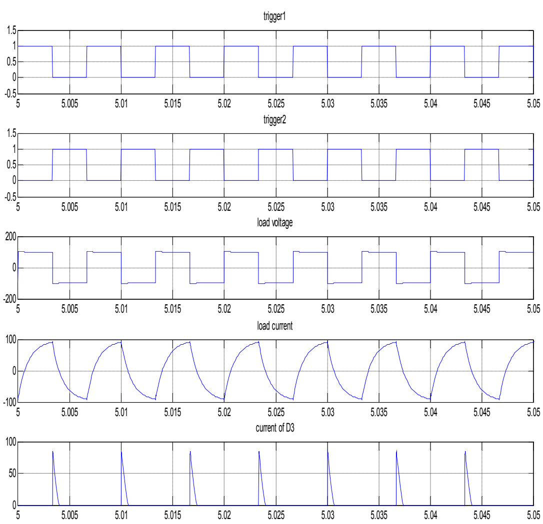

Fig2.PWM Inverter effect on Current & Voltage of power

IV. Conventional DC-DC Converters

Conventional DC-DC Converters are electricity transformation circuits focusing on the DC voltage using basic methods. They are popular in ordinary Drives and in applications where power-loss and temperature increase is not an important issue. They accept a DC voltage input and simply output another DC voltage value.

They mostly divided into three important categories:

- ✓ Step-Down (Buck) Converter
- ✓ Step-Up (Boost) Converter
- ✓ C'uk Converter
- ✓ Push-Pull Converter

Push-Pull converters are defined as two single switch converters (forward) that have the advantage of no need to an isolated power supply to drive the MOSFETS. The transformer works at both of the quadrants and gets resets at each cycle. In Fig.3 a schematic of the designed push-pull converter is simulated and in next Figure (Fig.4) the practical model of this converter is visible.

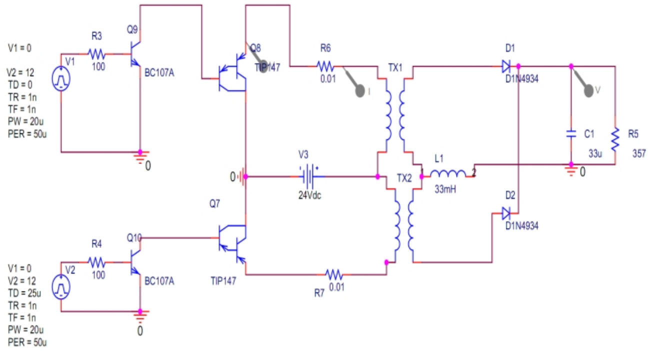

Fig.3. Push-Pull Converter Simulation Schematic

Push-Pull Converters are not so common because of the flux walking phenomena. In each cycle the flux moves toward state of saturation because MOSFETs may be turned on for a longer time and flux wing on transformer due to its V/Sec. Push-Pull converters are quite cheap and they can sense peak currents. Transformer is smaller than the forward converters and is similar to half and full bridge topologies.

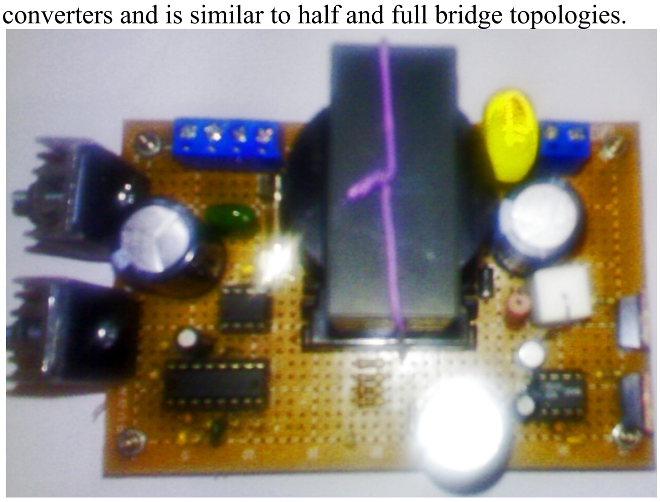

Fig.4. Practical Push-Pull Converter

V. ZCZVTF Soft Switching

Soft switching can mitigate some of the mechanisms of switching loss and possibly reduce the generation of EMI. Zero current and zero voltage switching systems switch the energy on or off at the zero point of the AC cycle, so the electrical interference is reduced, as well as the stress on the

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switching components. The efficiency also improves. A half bridge is two switches in series across a supply (typically DC), with the transformer primary connected between the point where the switches are joined and power common.

The switches operate alternately, so the voltage across the transformer primary is the supply voltage. The full bridge is two half bridges, with the transformer primary connected between the two half bridges. In the first half cycle the current flows from the supply, through the upper device of one side, the transformer primary, and through the lower device of the other side. The current flows through the other two switches during the second half cycle. The voltage/current in the transformer primary is reversed, so the transformer primary has equal of twice the supply voltage. Semiconductor devices are switched on or off at the zero crossing of their voltage or current waveforms:

- ✓ Zero Current Switching: transistor turn-off transition occurs at zero current. Zero-current switching eliminates the s witching loss caused by I GBT current tailing and by stray inductances.

- ✓ Zero Voltage Switching: transistor turn-on transition occurs at zero voltage. Diodes may also operate with zero-voltage switching. Zero-voltage switching eliminates the switching loss induced by diode stored charge and device output capacitances.

The main advantage is that the current through the switches is approximately half for a given power and supply voltage. Advantages are doing with a greater level of control of the waveform, which include zero switching and properly balanced waveform.

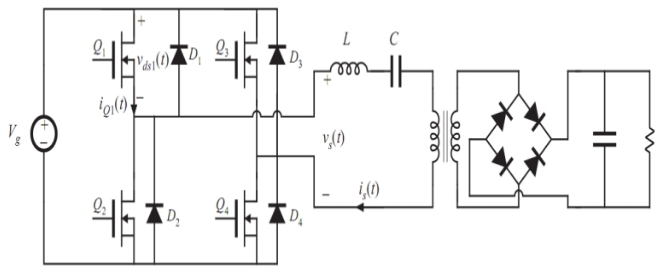

Fig.5. A Full Bridge conventional DC/DC power Converter

The PWM part is pulse width modulation, varying the on/off ratio in each cycle to vary the power. If the waveform is not symmetrical (the same in each half cycle), there will be a DC component, so this needs to be considered for the transformer. A full bridge can make both half cycles balanced by having a suitable off period, called dead zone.

Condition Sequence for a conventional ZVT Converters is as follows: D_1-Q_1-D_2-Q_2 , and so Q_1 is turned on during D_1 conduction interval, without losses. Zero-voltage s witching is usually preferred in modern converters. Zero-voltage transition converters are modified PWM converters, in which an inductor charges and discharges the device capacitances. Zero-voltage s witching is then obtained.

A. Zero-Voltage Transient Converter VI Diagram

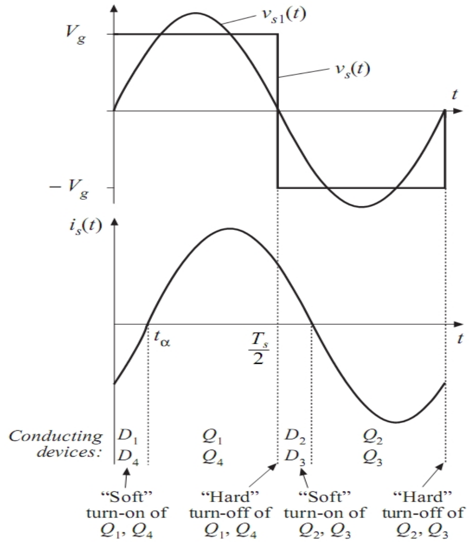

Fig.6. ZVT Converter Sequence Switching

B. Zero-Current Transient Converter VI Diagram

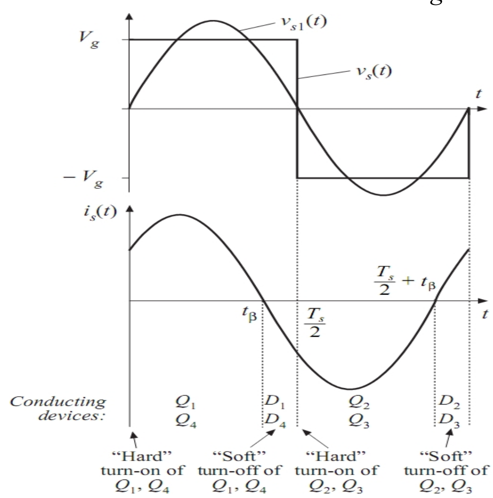

Fig.7. ZCT Converter Sequence Switching

VI. SOFT SWITCHING PWM CONVERTER- DC COMPRESSORS DRIVES

In industry, most compressors DC drives are desired to be small, cheap and light. To be able to minimize the size and weight of usual converters, a high switching frequency in converters is vital; but, at high speed switching frequencies, the switching losses up rises significantly. Soft switching procedures are proper solutions to reduce switching losses in order to apply power converters in high switching frequencies. [5] There are 3 known techniques to do this: 1st, Zero voltage transition (ZVT); 2nd, zero current transition (ZCT) and finally active clamp techniques that all can reduce switching loss while control circuit is still PWM. [6]

An important problem in using converters in compressor drive applications is the energy loss of transformer leakage inductance that causes huge voltage spikes against converter switches at switch off cases and heats up the drive. Soft switching techniques like zero current transition technique are suitable and proper solutions to bring up soft switching for PWM converters used in these drives and to overcome disadvantages discussed by transformer leakage energy inductance. Using the zero current transition technique in

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order to isolate converters can minimize the energy of transformer leakage inductance to nearly zero and prevent voltage spikes though. In most previous Zero Current PWM Converters, it's a must to have a resonant inductor. [7] Also, the PWM Switch is off because of transformer magnetizing inductance current and so zero current switching condition is not fully provided for the main PWM switch. [8]

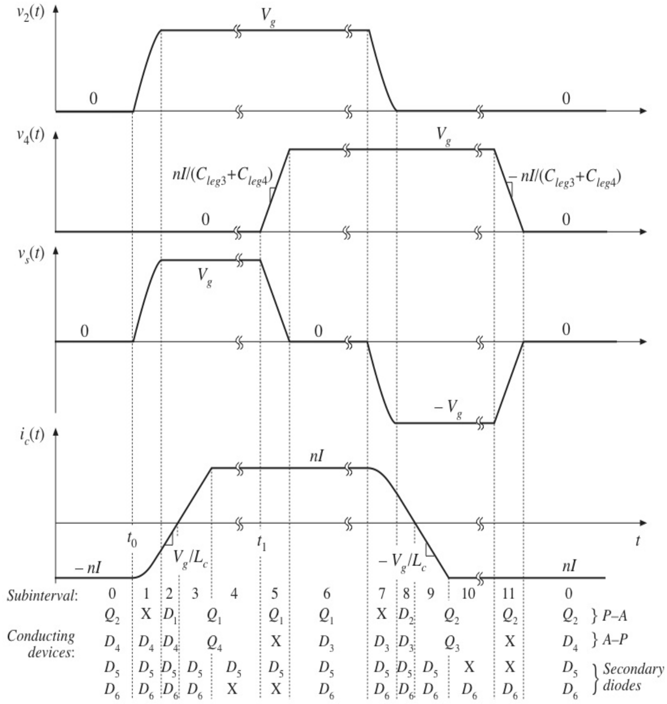

Fig.8. The expected conventional voltage and current theorotical diagram in ZCT PWM Converter

As it is obvious in comparison between theorotical and realistic results of simulation, using DC/DC converters can absoloutly be considered to control the voltage leval of supply feeder in a DC motor and hence controlling it's net torque and speed. DC/DC converters are operating the same role as PWM-VSD drives for asynchronous motors. It is possible to use a Flyback converter instead of a forward converter in some applications with higher priority, but the net cost of the manufacturing will increase due to need to a transformer instead of an inductor. In Forward converter Energy goes from the input, through the magnetics and to the load, simultaneously butin a FlyBack method, Energy goes from the input and stored in the magnetics, Later, it is released from the magnetics to the load.

A zero-current/zero-voltage switch (ZCS/ZVS) where each switch cycle delivers some amount of energy to the converter output, and switch turn-on and turn-off occurs at zero current and voltage, resulting in an essentially lossless switch. This reduces EMI in power supply by two methods:

- ✓ By switching the bipolar switch when the voltage is at a minimum to minimize the hard switching effect that causes EMI.
- ✓ By switching when a valley is detected, rather than at a fixed frequency, introduces a natural frequency jitter that spreads the RF emissions spectrum and reduces overall EMI.

The auxillary in the propsed method is reducing EMI with decreasing the hard switching condition to the lowest level possible. The auxillary circuit increases capability to save energy and consuming it to the output when essential.

VII. Considerations Discussions

A. Advantages of VSD-PWM , DC-DC PWM usages in reliability and economic aspects

The 3 Phase Induction Motors fed by Variable Speed drives based on VSI-PWM or DC drive fed DC-DC Converters may have to support 3 main extra stress factors that are described as internal temperature up rise, partial discharges losses and breakdown in stator windings insulations. The use of variable speed compressors increases the level of system reliability. Generally, the pick of the absorbed currents are lower in regards to the chance of starting the inverter driven compressors at lower speeds and reducing the number of on and off procedures which are one of the main sources of mechanical and electrical stress. The internal temperature up rise is mainly because of the harmonics increase which leads to a significant rise in iron and copper losses and, so, the overall losses will increase. Note that main control techniques are being developed in new style VSI PWM VSDs to reduce harmonics, specially on the motors but because of the temperature increase, partial discharge and voltage stress applied, the insulation of these motors with long cable runs may have a shining shortened life time when drived by VSI PWM VSDs.

In general, the Highlighted Benefits of variable speed compressors and DC/DC converters used in DC motors are: an increased efficiency at partial loads due to the fact that continuous regulation of the cooling capacity could be adapted to the load level, and to the installation of two parallel compressors on the same cooling circuit. Regulation of the cooling capacity over a wide operating range is another important advantage, i.e. from 10% to 100% consequently, Higher accurate cooling temperatures levels (±0.2°C), due to continuous regulation of compressor's currents using inverters and Reduction of the net absorbed current, cause the inverter maintains a constant power factor to the compressors it is connected. Limitation of the peak absorbed current is important since the inverter driven compressor can always be turned on at a lower speed, Limitation of noise emissions at partial and half partial loads (i.e. during low load and night time operations) are among useful advantages for consumers and finally Increased system reliability in regards to the reduction in compressors turn on and off's and limiting potential stresses. [10]

B. Considerations of lubrication, cooling, Parallel usages of PWM-VSD / DC-DC Driven Compressors

A further important subject regarding VSD or DC/DC drives is the proper lubrication of the compressor. It should be considered that in order to ensure correct oil circuit in a cooling procedure with one or more compressors operating in parallel, they must be connected to an oil level stabilizer, with correct amounts of suction and discharge in piping. In this way, the compressors act as if they were a single compressor, allowing for improved lubrication action. In a system which has a variable speed drive compressor operating in parallel with one or more fixed speed compressors in role, oil equalization should not be implemented since the VSD or DC/DC drive compressor generates differences in suction pressures leading to different oil levels. Because of these reasons, PWM inverter

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driven compressors (VSD drive or DC) should not, be installed in parallel with other compressors, which would mean losing the benefits of "tandem" operation at partial loads. [3] By using multi compressors connected to each other in parallel on the same designed cooling circuit it will be possible to increase energy efficiency at partial loads consumptions in compared to multi-circuit units. The main heat exchangers are sized for the full capacity of the unit therefore, and so when the compressor is operating at partial loads, the heat drops in the exchangers reduce (due to a significant increase in the evaporating temperature and a decrease in the condensing temperature tough), providing improved efficiency level compared to the full load operation. Ensuring correct oil return in pipes in a cooling circuit with one or more compressors operating in parallel at a fixed speed is a rather critical question which has usually been resolved by allowing the compressors to communicate with the oil equalizer in same time and with suitable diameters of the suction and discharge oil tanks. [2] Hereby, the compressors operate almost like they were one single compressor and the oil level is somehow the same for all of compressors allowing optimum lubrication procedure. [3]

VIII. Energy Consumption and CO_2 Emission

Many parameters need be changed to change energy consumption continuously. Changing the needs by mechanical means is usually very inefficient. With VSD or DC/DC, this goal can be achieved by varying the motor speed. This saves lots of energy cause the shaft power is mainly proportioned to the flow rate. On the other hand, the power loss ride-through function is used if the input supply voltage is down. In such a situation, the AC or DC drive will continue to operate using the kinetic energy of the running motor. The drive will be fully operative as long as the motor is running. [1] The primary start current of a compressor is six times more than the usual necessary current and this will lead to a significant waste of Energy. Using a VSD or DC/DC drive in this case could avoid energy loss. This is because both of them change speed based on load level.

IX. Conclusions

VSD - DC/DC usage to drive compressors allows controlling and accurate measurements on speed and torque of compressor motors, and so enhancing its application characteristics. Integrating of VSD-DC/DC systems in compressors have significant technical and economical advantages including significant energy savings, and consequently the related reductions in CO_2 emissions, are possible through usages of these drives in a wide variety of applications in industry. In addition, in order to omit the energy losses in DC compressors, a new zero current transition PWM forward inverter is introduced, which applies a basic but vital auxiliary circuit. The inverter is analyzed; design and considerations have been discussed.

Modifications

This paper has been revised on 15/05/2012 to modify few errors made in the original version of the paper. The original paper used a ZCTF converter directly which in fact better not to be used in such applications; ZVTF is preferred here.

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Saeed Jahdi (IEEE Member'10 – No. 91249721 , IAENG Member – No. 113076) received his BSc degree (1st) in Electrical Power Engineering; from department of Electrical and Electronic Engineering in Iran University of Science and Technology in August 2010 in Tehran. He afterwards received his MSc (With Distinction) in Power Systems & Energy Management from City University London**,** School of Engineering and Mathematical Sciences in January 2012. Mr. Jahdi was a MATLAB teacher till August 2009 in IUST and he has done a few projects to simulate the parameters of Electrical Machines in IUST. He has several publications in relevant fields as well. Mr. Jahdi is a current member of Both IEEE and IEEE societies of Power and Energy, Systems, Man & Cybernetics and Power Electronic and also IAENG and IAENG Electrical Engineering society.

Loi Lei Lai received his BSc (First Class Honours) and PhD from University of Aston in Birmingham, UK. He also received a higher Doctorate, DSc from City University London (CUL), UK. Currently Prof Lai is the Head of Energy Systems Group and Chair in Electrical Engineering at CUL. He is also Visiting Prof. at Southeast University Nanjing and Guest Prof. at Fudan University, Shanghai, China. He was awarded an IEEE 3rd Millennium Medal, in 2000 IEEE Power Engineering Society UKRI Chapter Outstanding Engineer Award and 2003 IEEE Power Engineering Society Outstanding Large Chapter Award. In June 2006 and July 2009, he was awarded a Prize Paper by IEEE Power and Energy Society Power Generation and Energy Development Committee. In 1995, he received a high-quality paper prize from the International Association of Desalination, USA. Now, he leads the technical research of the multi-million Euros project entitled South-East European Transmission System Operator Challenges which is sponsored by the European Commission's Seventh Framework Programme. He was the Program Committee Chair of the technically co-sponsored by the IEEE Systems, Man & Cybernetics Society (SMCS) 2009 International Conference on Machine Learning and Cybernetics. In 2000, he was the Conference Chair of the IEEE PES/IEE technically co-sponsored International Conference on Power Utility Deregulation, Restructuring and Power Technologies. He is a judge for the Power/Energy Category in the IET Innovation in Engineering Awards since the award began in 2005. He is an Editorial Board Member of IET Generation, Transmission, Distribution & Vice President for Membership & Student Activities of SMCS. Prof. Lai is a Fellow of both IEEE and IET.