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Current Control of a 3-Level Rectifier/Inverter Drive System

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Abstract: *The marriage of a three-level voltage source inverter with a force-commutated three-level rectifier is examined in this paper. Three-level inverters are capable of reducing the output current harmonics dramatically compared with typical two-level inverters whereas a three-level rectifier of this type allows nearly sinusoidal input currents at unity fundamental power factor on the utility side of the drive system. The dual capacitor, split voltage bus can be regulated from either the inverter or rectifier side with neutral point balance maintained. This paper address the issues of neutral point voltage control and current regulation from both the rectifier and inverter perspectives.*

I. INTRODUCTION

Three level inverters have been in existence for over a decade and have traditionally been fed by thyristor or diode rectifiers. However, an investigation of a complete three-level drive system does not appear to have been undertaken. By coupling a three-level rectifier to a three-level neutral-point-clamped (NPC) voltage source inverter (VSI), a complete three-level drive system can be implemented as illustrated in Fig. 1. This drive system utilizes a split capacitor DC link and a common control computer for both input and output side converters.

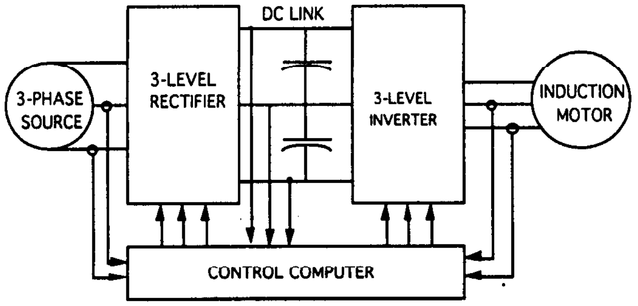

Fig. 1 Block Diagram Of 3-Level Drive

For balanced system operation, the midpoint of the dc link must remain clamped at one half the complete dc link potential. Should the "neutral point" deviate too far from this voltage, an uneven voltage distribution on the switches will occur, which could clearly lead to premature failure of the devices in the converter. This complete three level topology thus requires a thorough investigation of the issue of how the currents in the two converters can be controlled as to maintain balanced voltages on the switches in the most effective manner. This paper is therefore concerned with two major issues:

- Neutral Point Control

Numerous strategies have been used to maintain the neutral point voltage at one half the dc link maximum. One particularly effective solution utilizes the redundant voltage states in the voltage state diagram. In both the rectifier and inverter, the non-zero redundant states differ only in the direction of the current flowing in the neutral. By utilizing the neutral point voltage as feedback, correction for drift in the neutral point can be continuous. Neutral point control can be achieved from either the rectifier or inverter, and the most suitable means for neutral point control must be established.

- Input and Output Current Regulation

For field oriented control of ac machines, the VSI requires current regulation capability. A variety of current regulation strategies have been successfully applied to three-level NPC VSI's, of which space vector regulation has been shown as one of the most promising [2]. Also, it is necessary to draw unity fundamental power factor with minimal current harmonics from the utility to meet industrial power quality standards, such as IEEE 519. With application of space vector current regulation techniques to the circuit in Fig. 1, unity fundamental power factor input can be easily achieved with several rectifier topologies.

II. THE THREE LEVEL NEUTRAL POINT CLAMPED VOLTAGE SOURCE INVERTER

The three-level NPC inverter, introduced in 1981 [3], has been demonstrated to provide significant benefits compared to normal two-level voltage source inverters at high power levels. The benefits of the 3-level VSI include substantially reduced output current harmonics as well as the ability to essentially double the dc link voltage using switches of a given voltage rating. The 3-level VSI normally operates with a split-capacitor dc link as illustrated in Fig. 2. The four switches in each leg of the inverter allow complete control of the output voltage, and numerous types of PWM control strategies have already been applied to this circuit [2,3].

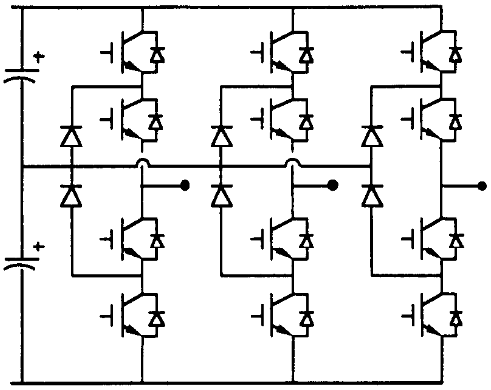

Fig. 2 Conventional Three Level Neutral Point Clamped Inverter.

It has been shown that the three level inverter itself has 27 switching states, of which 19 are unique [2]. These states are conveniently illustrated by the diagram of Fig. 3, defining a d-q space vector plane of operation. Space vector current regulated pulse width modulation (CRPWM) utilizes knowledge about the induction machine and feedback information to determine the equivalent fundamental component of internal emf of the machine. This emf voltage is portrayed as a vector in the d-q plane of the inverter. The tip of the voltage vector lies in a small triangle in the d-q plane, as defined by the nearest switching states of the inverter. Switching of the inverter is initiated based upon the present location of this emf voltage vector and the orientation of the current deviation vector obtained from the difference of the actual line currents and the generated current references.

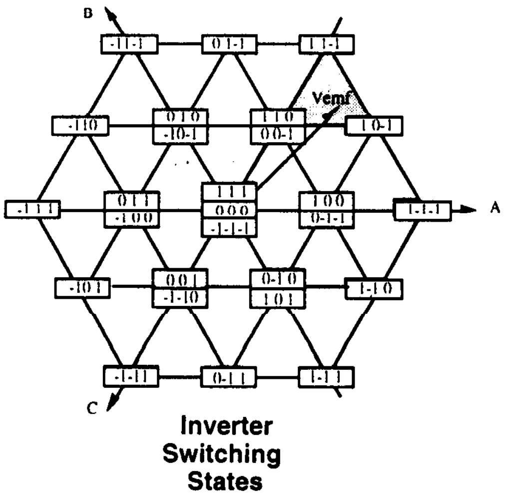

Fig. 3 Possible NPC Inverter Switching States

This so-called "adjacent-state" space-vector CRPWM has been shown to be a very desirable control strategy from the standpoint of fast current regulation and minimum current harmonics. Under normal operating conditions, the inverter operates with minimum switching losses because of the adjacent state operation.

III. THE 3-LEVEL FORCE-COMMUTATED BOOST-TYPE RECTIFIER

A more recently introduced three level boost type rectifier is illustrated in Fig. 4 [1]. As illustrated, each leg of the rectifier consists of four diodes and only two switches, and importantly, the entire rectifier again feeds a split capacitor dc link. This arrangement allows the maximum utility potential to be impressed upon either of the capacitors in the dc link. Each diode and switch in the rectifier again nominally sees only half the maximum dc link voltage. Thus the maximum dc link voltage can again be doubled. The circuit configuration is immune to possible shoot-through because of the presence of the diodes, which clearly enhances circuit reliability.

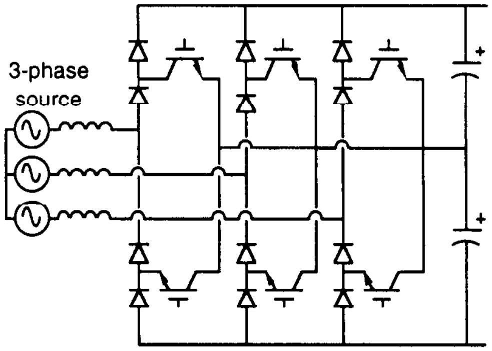

Fig. 4 Partially Active Three Level Rectifier

Similar to the three-level NPC inverter, this new three-level rectifier has 19 unique voltage states derived from 27 possible switching modes. Unlike the NPC VSI, however, not all states are permissible operating points at all times. Hence, the term "partially active" is used to represent this new converter and distinguish it from the NPC converter of Fig. 2 which also is capable of rectifier operation. Because the diodes normally conduct the main power instead of the switches, the region of permissible operation is defined in the d-q plane by the location of the current vector. As illustrated by Fig. 5, the current vector determines a small hexagon of possible operating states. The allowable operating region rotates around the voltage plane as the current vector rotates. The current regulation capability of the rectifier is somewhat limited by this restricted operating region, but it will be shown that excellent operating characteristics can be still be achieved. The rectifier achieves a boost action using the source inductances, and the maximum output power of the converter becomes a function of the source inductances [1].

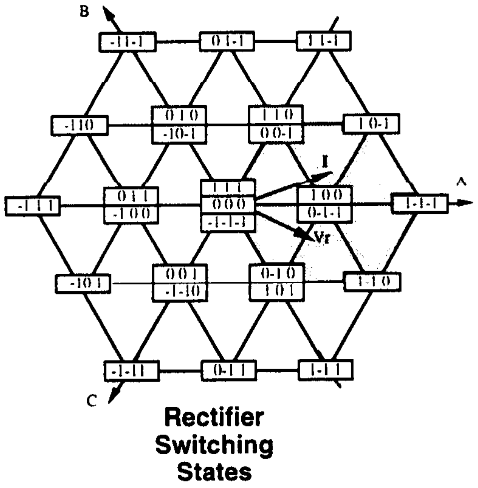

Fig. 5 Permissible Switching States for Three Level Rectifier

Alternatively, a second type of rectifier can be constructed using switches in place of diodes and vice-versa resulting in a rectifier version of the NPC inverter. This topology, referred to as the fully active three level rectifier, removes the limitation of voltage states imposed by the current vector considering the diode case. Utilizing switches in place of diodes also allows regeneration to be achieved.

IV. NEUTRAL POINT CONTROL

In a field oriented control system, the inverter controller has information about the rotor linkage flux and the machine parameters making determination of the equivalent fundamental terminal voltage vector possible. This vector is placed in the plane of the inverter switching states and the tip of this vector locates a small triangle, of which the vertices are the possible switching states. In every small triangle in the d-q voltage state plane, there exists one or more redundant states. These states apply equivalent voltages to the load, but the orientation of the current in the neutral differs. In one state, the current flows out of the neutral effectively charging the lower capacitor of the dc link while effectively discharging the upper capacitor in the link. In the opposite state, current flows into the neutral of the dc link effectively charging the upper capacitor link and discharging the lower capacitor.

In Fig. 3, the voltage emf vector locates a small triangular region. In this example, there is only one redundancy in the three vertices of possible inverter switching states. In the normal course of operation, the redundant voltage state will be desired at some time yielding two switching options. When the state 110 is chosen, current flows into the neutral, effectively charging the upper capacitor in the dc link. When the state 00-1 is chosen, current flows out of the neutral connection in the dc link effectively charging the lower capacitor in the dc link. With the neutral point in the dc link maintained at one half the maximum link voltage, both of the switching states applies the same voltage to the load. The redundant states will be selected on a regular basis. Continuous neutral point control can be achieved by monitoring the actual neutral point voltage and switching to the correct redundant states according to the direction of the neutral point drift. This continuous control comes at the expense of a slightly higher switching frequency.

Neutral point control achieved by the three level partially active rectifier is more complicated because of the dominant diode nature of this converter. As previously described, the possible voltage states of the rectifier are limited to a small hexagon by the orientation of the current vector. In each small hexagon, there are three redundant states capable of effecting the neutral point of the dc link. To maximize the neutral control capability of the converter, these redundant states must be selected as often as possible. This is accomplished by considering the equivalent terminal voltage vector of the rectifier. The voltage vector falls in either the upper half or lower half of the hexagon dictated by the current vector. Fig. 6 illustrates one example of rectifier switching determination for neutral point control.

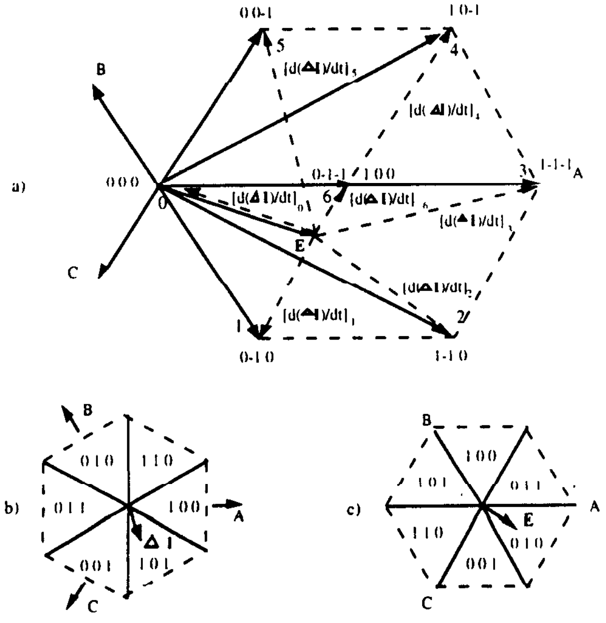

Fig. 6 Switching Strategy for Neutral Point Control

The small hexagonal region of operation was determined by examining the instantaneous position of the current vector on the d-q plane and is depicted by Fig. 6 a. The orientation of the current vector and current deviation vector are determined according to Fig. 6 b. In this example, the equivalent terminal voltage is located in the lower half of the region of operation illustrated in Fig 6 c. To exercise sufficient neutral point control, it is necessary to limit the regions of switching to the lower half of the hexagonal operating region. With this strategy, it becomes possible to switch to the redundant state for three of the six possible current regulation switchings. In our example, when the current deviation vector is located in the quadrants 011, 001, or 101, one can switch to one of the redundant states (0-1-1 or 100) depending upon the present condition of the neutral point determined from a feedback signal. This methodology sacrifices some current regulation capability in order to achieve neutral point control.

V. NEUTRAL POINT CONTROL SIMULATIONS

To investigate the behavior of the system under a wide range of conditions, the complete three level motor drive system was simulated. Four different operating scenarios were considered:

- Partially active rectifier controlling the neutral point with the inverter operating to produce a minimum switching frequency
- Inverter controlling the neutral point with the partially active rectifier operating to regulate current with maximum response
- Both the partially active rectifier and inverter operating to control the neutral point of the dc link
- Fully active rectifier (same topology as the NPC inverter) controlling neutral point with inverter operating to produce a minimum switching frequency.

All four scenarios were initially considered under typical operating conditions with current regulation maintained on both the input and output sides. The simulations represent a 250 kW drive system operating from a 460 volt three phase source. The dc link voltage level was regulated using a PI regulator to adjust the current references of the line side rectifier. A 1200 volt dc link was simulated with a 600 volt neutral point. Regardless of the neutral point regulation scheme, the neutral point was maintained at one half the dc link potential. The amount of ripple observed on the dc link is a function of the link capacitor size and was relatively independent of the neutral point control method used.

Under ideal conditions, the entire drive system is symmetric and balanced and no noticeable drift of the neutral point was experienced. The neutral point correction action of the rectifier or inverter only comes into play with an unbalanced system. One imbalance in the system immediately affecting the neutral point is a mismatch of capacitors in the dc link. Considering manufacturers typically rate capacitors at a given value +/- 5%, this type of mismatch is very realistic. To illustrate a typical mismatch, the three level drive system was simulated with one capacitor in the dc link having 90% the capacitance of the other -- a 10% capacitance mismatch. With current regulation maintained on the input and output sides, the four methodologies were examined. In all cases, the neutral point in the dc link was readily maintained. Fig. 7 below, illustrates the dc link voltages with the 10% capacitor mismatch and the neutral point maintained by the correction action of the inverter. This is an illustrative example, because the neutral point was also equally well maintained by the partially active rectifier, or by both the inverter and partially active rectifier working together, or by the fully active rectifier. A slightly increased ripple on the dc link voltage was observed as expected with the reduced link capacitance.

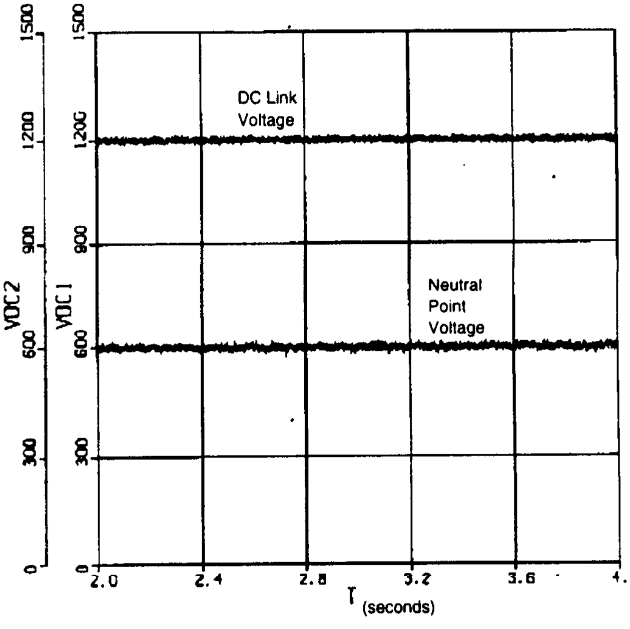

Fig. 7 DC link voltage with neutral point voltage with inverter control of neutral point while operating unsaturated with 10% dc link capacitor mismatch.

The second case of importance is system operation with the inverter saturated and current regulation of the output current lost (field weakening operation). This is an important case because the methodology for neutral point control from the inverter side relies upon the redundant states in the voltage state diagram. When the inverter becomes saturated and operates in the equivalent of six step mode, the inverter does not switch to the redundant states. As a result, neutral point control cannot be maintained from the inverter. Figure 8 below illustrates the drift of the neutral point voltage from the expected 600 volts, with inverter saturation and a 10% capacitance mismatch. It is obvious that the neutral point voltage has drifted substantially.

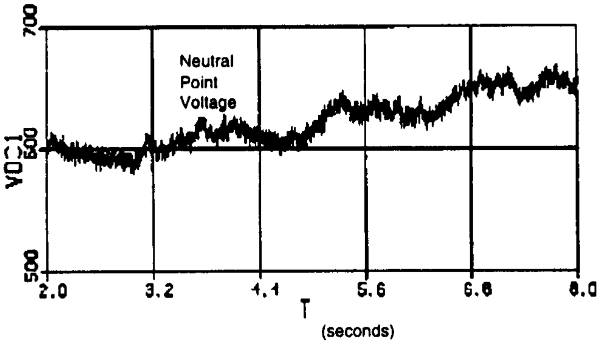

Fig. 8 Example of neutral point voltage drift with 10% capacitor mismatch with inverter controlling neutral point operating saturated.

Neutral point control can still be maintained from the rectifier side of the link when the inverter saturates. There will consequently be increased ripple on the dc link with the inverter saturated, but neutral point control will not be lost. Because of the importance of the input current regulation for minimizing utility harmonic pollution and maximizing power factor, the rectifier will be designed to maintain current regulation and can always be used to control the neutral point.

In the simulation study of the fully active rectifier, the neutral point was equally maintained compared with the diode-based three level rectifier in both the unsaturated and saturated inverter cases. Because of the desirability of minimal utility pollution, the rectifier was always operated with full current regulation. It practice, either an active or partially active three level rectifier would be implemented in such a manner so as to avoid loss of input current regulation.

VI. CURRENT REGULATION

In typical field-oriented induction machine drives, output current regulation is essential for good performance. The performance characteristics of space vector CRPWM 3-level VSI's have been thoroughly investigated. Excellent current regulation can be achieved until the inverter has reached its voltage limit whereupon the current regulator becomes saturated. In the saturation condition, the inverter operates essentially in a six-step mode and current control is lost. Loss of current regulation is not typically a catastrophic event, decoupling of the torque from the flux is no longer achieved with associated loss of precise control.

With the increasingly strict standards on utility pollution, the ability to draw unity fundamental power factor with minimum current harmonics is a premium. The 3-level active and partially active rectifiers operate in a similar manner as a three-level inverter. Three reference current signals are produced and the converter switches accordingly to produce currents following the current references. As previously indicated, there is a trade-off between control of the neutral point, already discussed, and current regulation. For maximum current regulation capability in the partially active rectifier, the switching strategy previously discussed would be dropped in favor of an improved strategy. The fully active rectifier would operate in the normal adjacent-state switching mode.

As previously illustrated, the main power of the partially active 3-level rectifier is through the diodes the operating region and is limited to a small hexagon dictated by the location of the current vector. To regulate the neutral point of the dc link, switching of the rectifier was performed to maximize the number of times the redundant states were chosen, utilizing the equivalent terminal voltage and dc link neutral point as feedback sensed variables. For maximum current regulation ability, the center redundant states are no longer utilized. Instead the points on the outer edge of the hexagon are chosen to maximize the current correction. This algorithm was simulated and proved to be very effective for maintaining current regulation.

VII. CURRENT REGULATION SIMULATIONS

Similar to the investigation of neutral point control, the entire three-level drive system was simulated under a variety of conditions. The four scenarios for the investigation of current regulation were identical to the neutral point simulations with different converters controlling the neutral point.

The initial simulations of this study considered the drive system with full current regulation maintained on both the utility input side and the output side. Again the simulation was a 250 kW induction machine drive operating at 0.8 power factor. On the output side of the drive, the neutral point control strategy implemented had no significant effect on the output harmonics. Output current regulation was achieved with a total harmonic distortion in the range of 5.5% to 6.5% with inverter switching frequencies in the 550 hertz to 750 hertz range. There was no apparent trade-off between neutral point control and the current regulation capability of the inverter.

On the input side, the choice of neutral point control strategy did have a significant impact on input current harmonics. When the neutral point was regulated from the inverter side and partially active rectifier was completely dedicated to current regulation, the input total harmonic distortion was on the order of 3.5% with an effective average switching frequency around 900 hertz. This switching frequency is easily within the switching capability of high power IGBTs and verging on the switching capability of GTOs. As soon as the rectifier control algorithm was switched to control the neutral point, the current regulation ability of the rectifier was reduced and the harmonic distortion of the input current increased to the 6.0% to 6.5% range. Switching frequencies were essentially constant.

When the inverter becomes saturated, it is operating in the equivalent of a six-step mode and it places a maximum burden upon on the dc link. As a result, the currents drawn from the dc link are at a maximum and any imbalances in the system will have their effect maximized. Because of the excessive demands upon the dc link, the rectifier has a more difficult time maintaining the link potential and regulating the input current. For conditions similar to the unsaturated case simulated, the input total harmonic distortion increased to approximately 8.8% for the case with the inverter switching algorithm operating with maximum current regulation capability and no neutral point control. When the rectifier was operating to control the neutral point, the input total harmonic distortion increased to be in the 12.0% to 12.5% range. These are significant increases compared to the case with the inverter operating un-saturated.

The differences in the current regulation capability based upon operating mode are readily apparent from the time domain waveform of the rectifier input current. Fig. 9 illustrates the input current waveform for the partially active rectifier operating for maximum current regulation with inverter operating unsaturated controlling the neutral point. In comparison, Fig. 10 illustrates the input current waveform for the partially active rectifier controlling the neutral point when the inverter was operating saturated. There is a dramatically observable difference between the two.

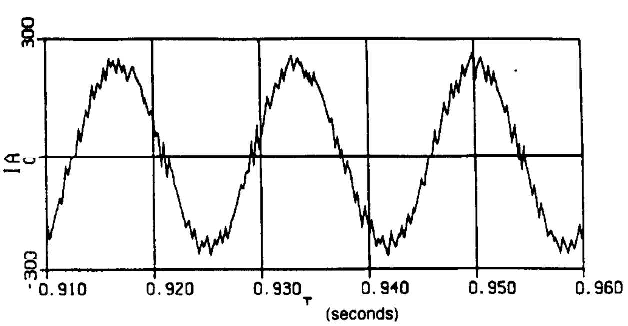

Fig 9. Input current waveform for partially active rectifier set for maximum current regulation with an un-saturated VSI controlling the neutral point.

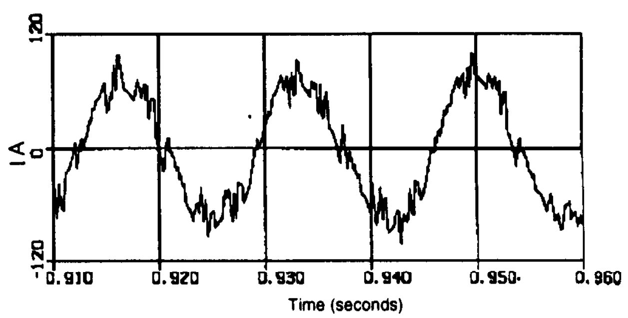

Fig. 10. Input current waveform for partially active rectifier controlling neutral point with inverter operating saturated.

In the final case of the fully active rectifier (all switches), current regulation was performed similarly to the inverter. Adjacent state switching was implemented to maximize current regulation response with a minimum switching frequency. For a given operational frequency, the fully active rectifier had roughly 25% poorer current regulation capability (a 25% increase in total harmonic distortion.). This appeared as a general trend regardless of system parameters and can be easily explained by considering the current correction capability of the respective converters from the d-q voltage state plane. The maximum correction capability for a given switching operation is a function of the distance between the tip of equivalent emf vector of the system and the voltage state being selected. This can be thought of as a correction voltage. With the fully active rectifier, with normal adjacent state switching, the correction voltage is relatively small. With the switching algorithms of the diode-based rectifier, the correction potential can be significantly larger because switching is not limited to the adjacent states.

While the exact total harmonic distortion and switching frequencies in the simulated cases are heavily influenced by the actual drive system parameters, several trends are nonetheless present. Illustrative total harmonic distortion statistics for the various simulated cases are summarized in Table 1 below. Control of the neutral point with a partially active rectifier increases the input current waveform distortion by almost a factor of 2 compared with the rectifier algorithm maximizing current regulation response. A fully active rectifier utilizing adjacent state control had worse current regulation capability than the partially active rectifier for a constant switching frequency.

Neutral Point Controlled from:	Input Current THD with Inverter Un-saturated	Input Current THD with Inverter Saturated
Inverter	~3.5%	~8.8%
Partially Active Rectifier	~6.2%	~12.5%
Inverter & Partially Active Rectifier	~6.4%	~12.2%
Fully Active Rectifier	~4.5%	~10.9%

Table 1. Summary of illustrative simulation results

In all cases for input and output current waveforms, there were no dominant current harmonics present other than the fundamental. Since the space vector current regulation algorithms are not based upon a high frequency carrier like sine-triangle modulation, the resulting current spectrum is devoid of harmonics appearing at discrete frequencies. Fig. 11 illustrates the spectrum of the input current with a partially active rectifier operating to control the neutral point with the inverter saturated, showing the relatively minimal harmonic content.

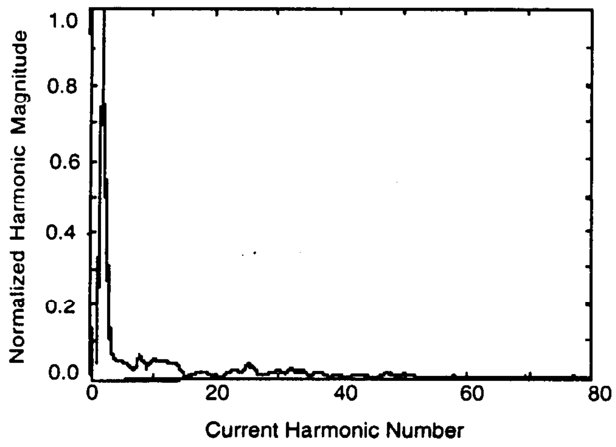

Fig. 11. Spectrum of input current of the partially active rectifier controlling the neutral point with the inverter operating saturated.

VIII. CONCLUSION

Circuit operation of a complete three level rectifier/inverter drive system has been investigated in this paper. It has been shown that using space vector current regulation techniques, excellent input and output current regulation characteristics can be achieved with excellent control of the dc link neutral point until the inverter becomes saturated. Neutral point control is accomplished utilizing the redundant states of the d-q state voltage plane to control the direction of the current flowing into the neutral point. Neutral point control can be readily accomplished from either the rectifier or inverter side, with essentially no effect upon the output current regulation capability of the drive system. However, when rectifier switching is used to control the neutral point, the input current regulation capability of the drive dramatically worsens and the total harmonic distortion of the input current roughly doubles with an essentially constant switching frequency. While neutral point control from the inverter has been shown to be superior, control from the inverter side is lost when the inverter saturates, requiring neutral point control from the rectifier side if neutral point drift is to be minimized.

From the standpoint of minimum utility pollution, it would be beneficial to normally have the inverter control the neutral point of the dc link switching to rectifier control of the dc link only when the inverter was approaching saturation. This would result in a minimum input current harmonic distortion possible while retaining control of the neutral point of the dc link at all times.

Overall, this topology has shown itself suitable for high power drive systems with the total benefits of:

- Unity fundamental power factor current drawn from the utility source.
- Minimal current harmonic pollution injected into the utility source.
- Output current regulation capability for field-oriented control applications.
- Doubled dc link voltage utilizing switches of a given device rating compared with a normal two level drive system.
- Maximum nominal voltage stressed place upon all devices is clamped to one half the dc link potential.

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