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Research Article

Bench Marking of Alternate Soft-charging Circuits for Variable-frequency Drives

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Abstract: This study presents about various soft charging techniques used in variable frequency drives to limit the in-rush current into the dc-bus capacitors during pre-charging condition. The main objective of a pre-charging circuit is to charge the capacitor within possible allowed time and maximum converter current without any voltage overshoot. A capacitor pre-charging circuit needs to be robust and simple in control by limiting the dc link inductor and input ac current to any desired magnitude. In this study we will discuss about various soft charging topologies, techniques and their performance during different operating conditions such as partially pre-charged capacitors, input line voltage variation, ground faults and bus faults. In the final this study discusses also about a novel pre-charging circuit, technique and provides a comparison of proposed technique with the existing techniques.

Keywords: Inrush current limiter, magnetic resistive-element, soft-charge circuits, variable frequency drives

INTRODUCTION

All Variable-Frequency Drives (VFDs) have large dc-bus filter capacitors to decouple the effects of inductance from the DC voltage source to the power bridge and also provide a low impedance path for the ripple current associated with hard switching of inverters. In older days to charge the dc-bus capacitors resistor-contactor arrangement were used to reduce and limit the inrush current during initial power up of converters and brown out conditions. The resistor-contactor arrangement provides a soft charging to the dc-bus capacitors. Because of the mechanical nature of the contactor, the reliability of the VFD gets adversely affected. Moreover, interrupting dc under certain circumstances can deteriorate the integrity of the contacts. Based on the above facts, soft-charging is one of the important area required attention on high power variable frequency drives.

Figure 1 shows different soft charging circuit configurations, as shown in Fig. 1b the resistor-contactor arrangement shown in Fig. 1a is replaced by the thyristor switch and resistor. During initial charging of dc-bus capacitor the thyristor switch will be kept in off condition, so the initial capacitor charging current flows through the resistor in order to reduce the inrush current and once the capacitor voltage reaches a steady state value the thyristor will starts conducting.

Later thyristor-controlled rectifiers have been used in VFDs as shown in Fig. 1c. In this topology, the input rectifiers are replaced by thyristors. The triggering angle of the thyristors are controlled in such a manner that the dc-bus capacitor charges up smoothly with no inrush current. When a brown out condition occurs, the thyristor angles are such that it provides the maximum output voltage possible, similar to a typical diode bridge. In Fig. 1d shows the soft charging circuit arrangement with MR element that shows high resistance under the influence of large magnetic field and low resistance when the magnetic field is low. The MR element could be connected in series with the dc-bus capacitor, to reduce the inrush current during start up and during the recovery time after a brownout condition.

This study discuss about comparison of different soft charging techniques and circuits used in VFDs to reduce the in rush current of dc-bus capacitor. The main focus for this comparison is as follows:

- To find a converter topology which can charge the dc-bus capacitor at all operating conditions
- To find a optimum converter topology in all aspect
- Suitable for high power applications

Theory of capacitor inrush currnet: Inrush current is a maximum, instantaneous input current drawn by an electrical device when first turned on. Power converters also often have inrush currents much higher than their steady state currents, due to the charging current of the input capacitance.

When a capacitor bank is initially connected to a voltage source a transient charging current will flow as

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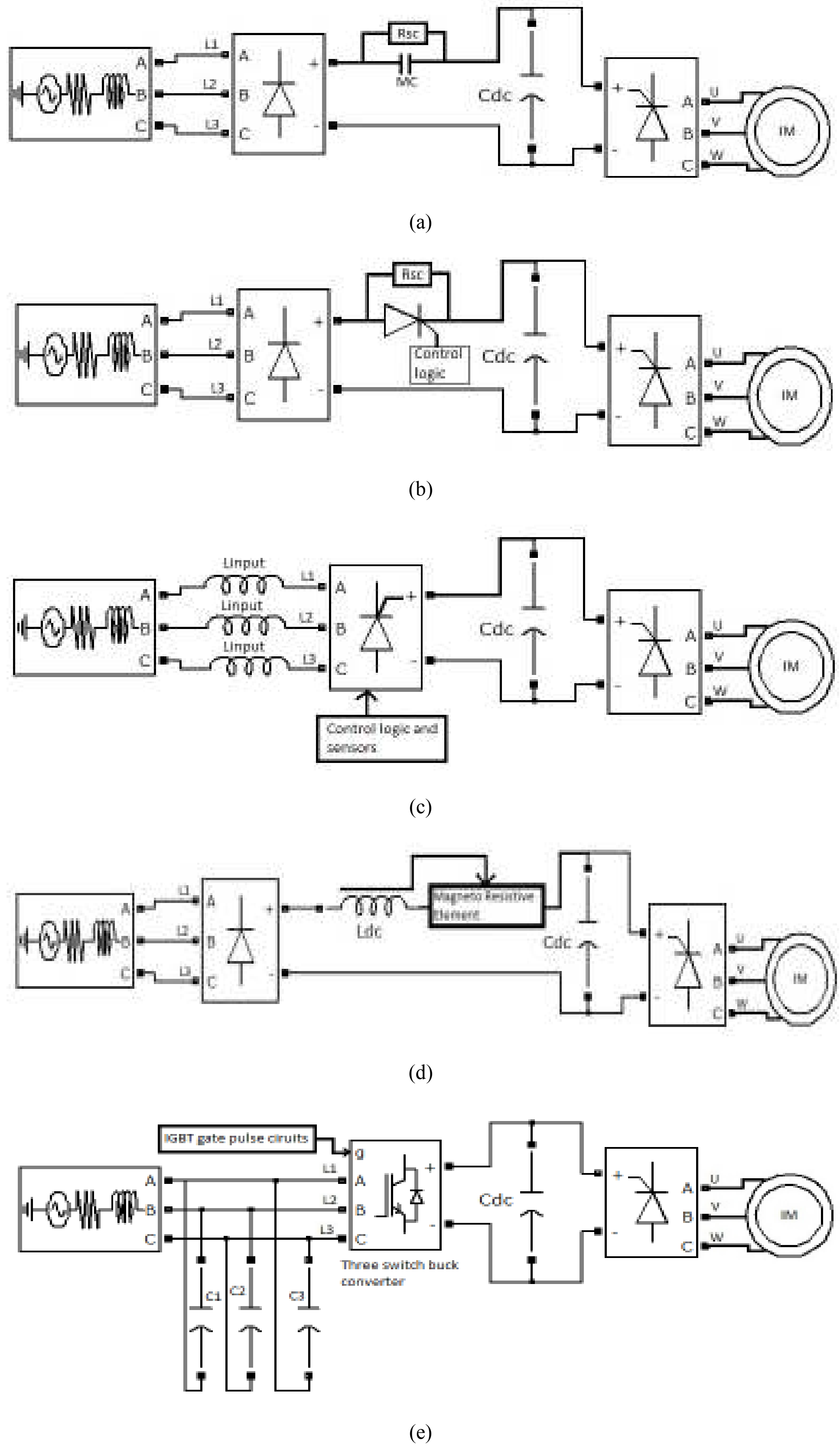

Fig. 1: Soft-charging circuit configurations; (a): With resistor-contactor; (b): With thyristor switch; (c): With thyristor bridge as rectifier; (d): With magneto resistance (MR) element; (e): Proposed three switch buck converter as rectifier

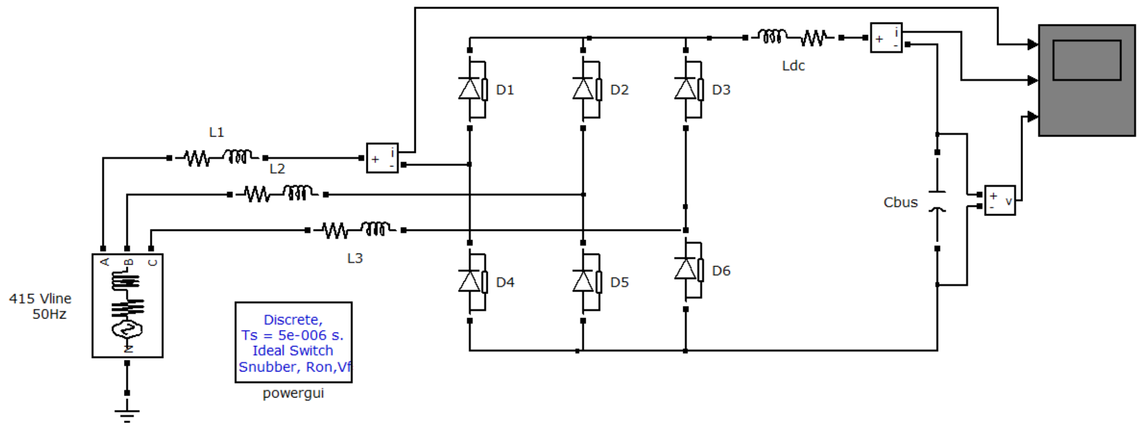

Fig. 2: Three-phase bridge rectifier circuit for capacitor current calculation

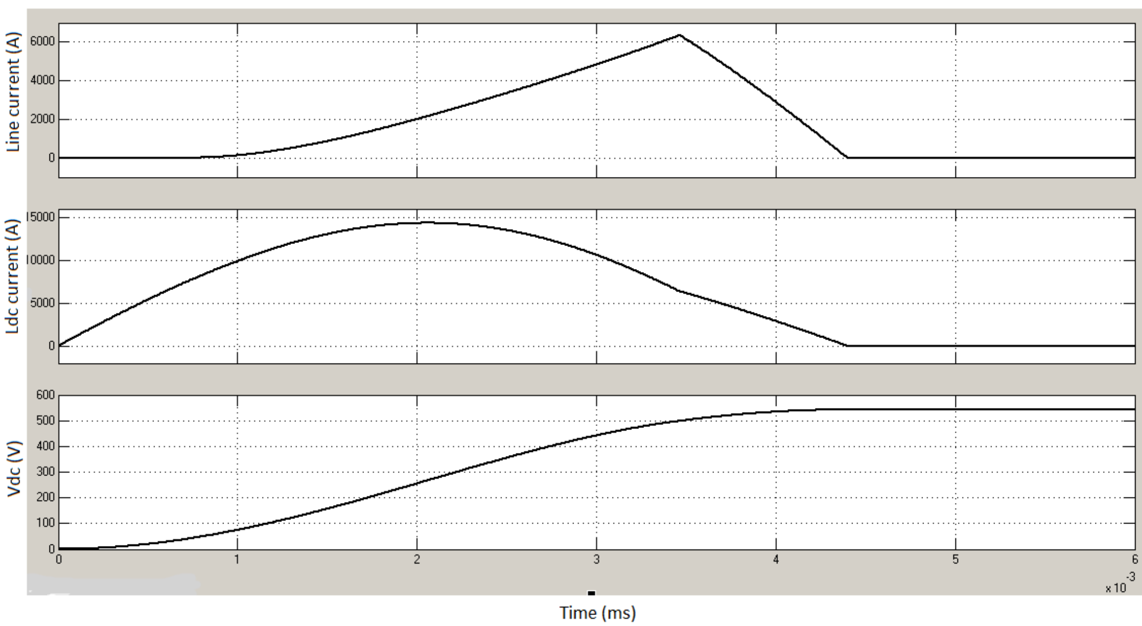

Fig. 3: Three-phase bridge rectifier circuit in-rush current and dc bus voltage

shown in Fig. 2. The magnitude and frequency of this charging current depends upon the total capacitance and inductance of the circuit as well as magnitude of the applied voltage. In calculations the crest value of the applied voltage is used, while the resistance in the circuit determines the rate at which this transient oscillation decays, it has only a negligible effect upon the initial magnitude and frequency of the transient. In practice the resistance is generally neglected. Experience has shown that inrush current of a single isolated bank normally range from 5 to 15 times the normal capacitor current as shown in Fig. 3.

STUDY OF ALTERNATE SOFT-CHARGING CIRCUITS

In this section we will discuss about different soft charging. Topologies, they are as follows:

- With mechanical contactor
- With thyristor switch
- Thyristor based rectifier
- With Magneto Resistance (MR) element
- Three switch buck converter

Mechanical contactor based soft charging circuits: The circuit shown in Fig. 1a depicts a soft charging circuit using mechanical contactor in parallel with a resistor bank connected in between DC link capacitor and diode bridge rectifier (Swamy *et al*., 2010). During initial switch on of the rectifier circuit the mechanical contactor is kept open, the capacitor is charged through the resistor bank connector in parallel to the contactor. Once the capacitor voltage reaches to a predefined voltage level the mechanical contactor is closed. The resistor banks are used to limit the capacitor charging

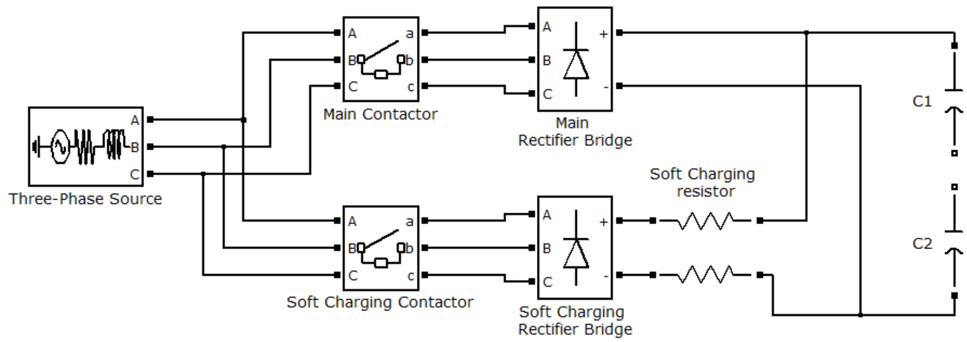

Fig. 4: Contact type soft charging in high power frequency drives

current and also to charge the DC link capacitors. Due to the high capacitor inrush current the resistor were connected in banks in order to dissipate the high power dissipation.

In high power frequency drives the mechanical contactor and soft charging resistor banks are connector as shown in.

Figure 4 during initial capacitor charging phase the capacitor inrush current flows through a separate soft charging circuit consist of contactor, Rectifier Bridge and soft charging resistor banks of less power rating and cost compared to having contactor and resistor banks in main current flow path.

Advantages:

- No power electronics (or) intelligent circuits required and simple in operation
- No current sensor required

Disadvantages:

- Huge resistor banks required
- Not possible to charge the capacitor during brownout condition and fault conditions
- High current DC/AC contactors
- More power dissipation and cost
- Welding of mechanical contactor

Thyristor based soft charging circuits: The circuit shown in Fig. 1b is a conventional thyristor based soft charging circuit which consist of conventional diode bridge rectifier at is input and thyristor bank connected between DC link capacitor and diode bridge rectifier (Swamy *et al*., 2010). A resistor bank is connected across the thyristor for initial soft charging. At initial charging the series thyristor is kept in OFF state and the capacitor gets charged through the resistor banks. The resistor banks slow down the sudden increase of capacitor charging current. Once the capacitor reaches to a steady state voltage thyristor will be switched ON through thyristor control circuit. By using this type of soft charging configuration the initial capacitor charging current will be limited to a safe limit through the resistor banks. During normal working condition thyristor will be in ON state to reduce the power dissipation (Fig. 5).

Advantages:

- Better controllability of capacitor charging current
- No current sensor required

Disadvantages:

- Huge resistor banks required
- Not possible to charge the dc-bus capacitor during brownout condition and fault conditions
- More power dissipation and cost due to additional high current thyristor banks and contactors

Thyristor rectifiers based soft charging: The circuit shown in Fig. 1c consists of a conventional SCR ac/dc converter with dc link capacitor (Gilmore and Skibinski, 1996). This circuit limits the peak dc and ac line currents to any desired magnitude during a drive pre charging mode without the need of any current sensor. Bus capacitor voltage is fed back to the feedback control circuit along with conventional zero crossing detection of the ac line to control the thyristor firing angle, so that dc-bus capacitor charges up smoothly with no inrush current. When a brownout occurs, the thyristor firing angles are in such a way to provide the maximum output voltage similar to diode rectifier. When the voltage recovers after a brownout condition, the difference between the peak value of the input voltage and the dc-bus voltage is large enough to force the firing angle to increase and hence reduce the high inrush current (Fig. 6).

Advantages:

- No current sensing/sensor required
- Possible to charge the capacitor during brownout condition and fault conditions through controlling the thyristor firing angle

Disadvantages:

- There is the need for six-pack thyristor modules.

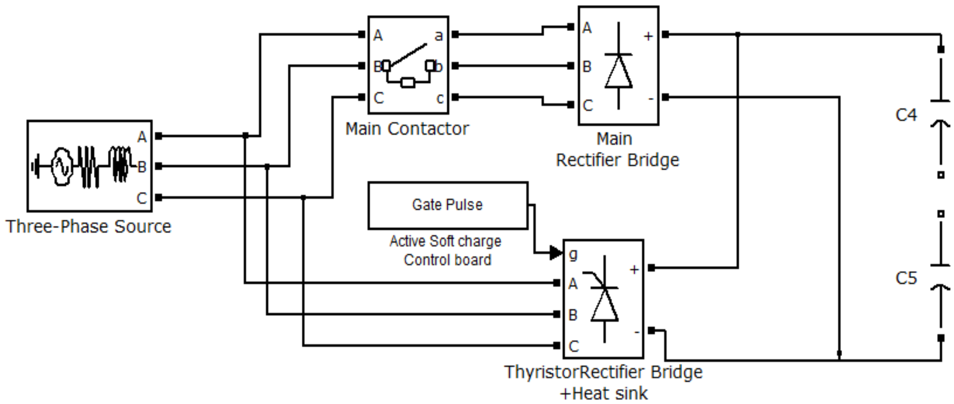

Fig. 5: Thristor based soft charging in high power frequency drives

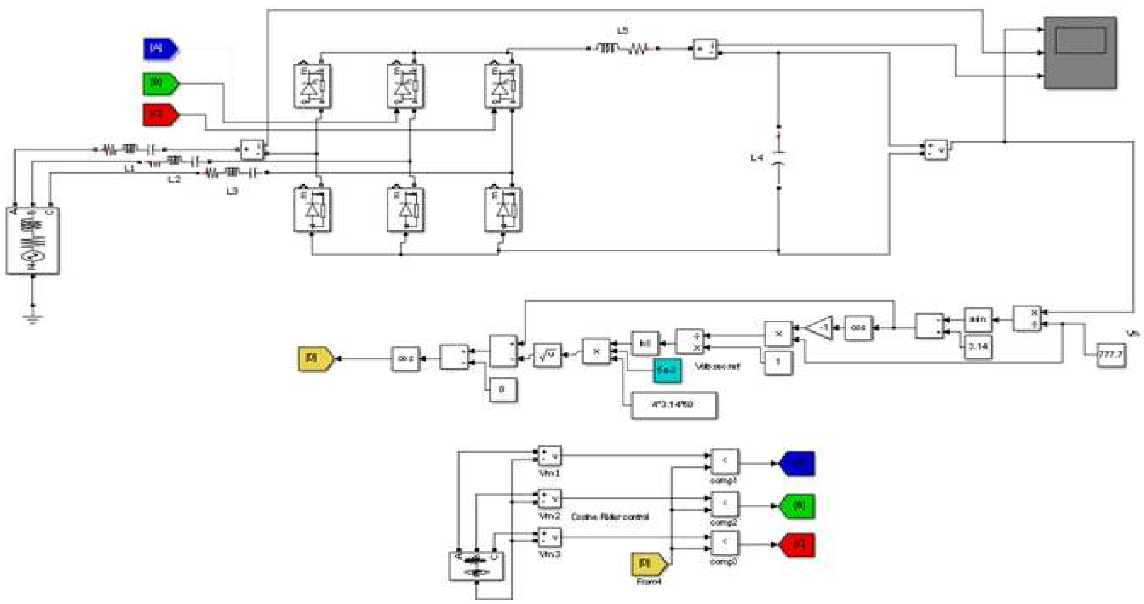

Fig. 6: Thyristor rectifier based soft charging with nonlinear firing angle control

- Six gate trigger circuits with sensing and decision making logic. The trigger and logic circuits occupy space and are expensive.
- The thyristor cause a voltage notching effect due to overlap phenomenon during commutation. This requires the use of an input ac inductor to reduce the notching effect on other equipments, this addition occupies space and will be an added cost.

MR-Element based soft charger: One of the topologies studied here includes the use of an MR device that shows high resistance under the influence of large magnetic field and low resistance when the magnetic field resets to a lower level (Swamy *et al*., 2010). The MR element could be connected in series with the dc-bus capacitor to soft charge it at startup or during the recovery time after a brownout condition. The circuit diagram is shown in Fig. 1d.

Advantages:

- No power electronics (or) intelligent circuits required
- Simple circuit for implementation
- No current sensor required

Disadvantages:

- Behavior of the MR element at an elevated operating temperature should be considered. Since most of the heat is produced in the air gap of an inductor, placing an MR element in the air gap needs careful study.
- Since rated load current has to pass through the MR element, this idea may be limited to small power due to the limitation of presently available MR materials. When the rated current increases, the MR element can become large and placing it in the air gap may pose a problem.

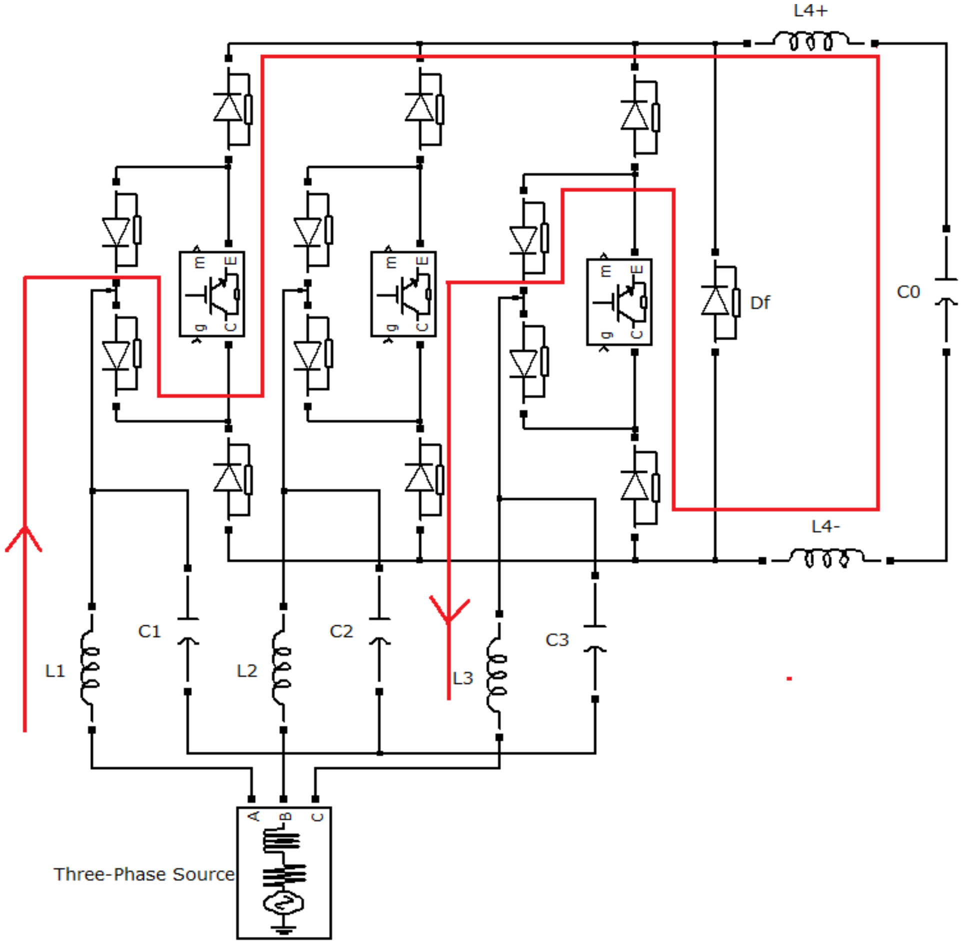

Fig. 7: Three switch buck converter based soft charger with S1 and S3 ON

Proposed three switch buck converter based soft charger: Figure 7 shows the three switch buck converter and its operation that is used for DC capacitor soft charging (Nussbaumer *et al*., 2007; Baumann and Kolar, 2001). As shown in Fig. 7 when the phase R is positive with respect to the phase T, the current will be flow through switch S1 and S3 through which the dc-bus capacitor will be charged According to the actual switching combination the dc link current I impressed by the inductor L_{4+}, L_{4-} is distributed to two of the input phases or the freewheeling diode D_F. The space vector of three-phase quantities is defined as:

$$i_{rec} = \frac{2}{3}\left(i_{rec,R} + e^{j2\pi/3} \cdot i_{rec,S} + e^{j4\pi/3} \cdot i_{rec,T}\right) \quad (1)$$

For the switching state j = (101) the rectifier input currents are $i_{rec,R} = I$, $I_{rec,s} = 0$ and $i_{rec,T} = -I$, therefore the rectifier input current space vector for the switching states will be:

$$i_{rec,(101)} = I.\frac{2}{\sqrt{3}} e^{j\pi/6} \quad (2)$$

$$i_{rec,(110)} = I.\frac{2}{\sqrt{3}} e^{-j\pi/6} \quad (3)$$

$$i_{rec,(010)} = 0 \quad (4)$$

Thus these switches will be switched in a control manner which will be used for charging the DC link capacitor.

Advantages:

- Only three IGBT switches required
- Simple control technique compared to nonlinear firing angle control
- Thyristor doesn't have control in case of fault once if they come in conduction. But here it will be immediately stopped if there is a over current fault is detected
- The gate drivers for the IGBT's are inexpensive and simple current sensor is required at DC link only

Disadvantages:

- Each gate driver requires isolation
- Components count will be higher

DIFFERENT CONTROL ALGORITHMS FOR SOFT-CHARGING

There are different control algorithms used for capacitor pre charging that limits both peak dc link and peak ac input line current within the desired limit thereby providing an optimum pre-charge control and robust operation.

Linear continuous current control algorithm: A linear current control technique can be used to solve the peak over-current and bus overshoot voltage problems. However, linear current control may be applied only up to the limit of dc link inductor current discontinuity as defined by the below Eq. (5) of conventional dc bridge rectifier:

$$E_f = \frac{3\sqrt{2}}{\pi} V_{line-line(rms)} \cos\alpha \tag{5}$$

The output voltage of the dc bridge rectifier (V_d) is the dc bus capacitor voltage which is feedback to the controller as (E_f). By controlling the controlled switch firing angle we can control the dc bridge rectifier output voltage as shown in the below Eq. (6):

$$\alpha[radians] = \cos^{-1}\left[\frac{E_f}{\frac{3\sqrt{2}}{\pi} V_{line-line(rms)}}\right] \tag{6}$$

Even through linear current control techniques reduces the peak over current and over voltage it has some undesirable characteristics and problems like device peak current stress, input fuse stress and unacceptable large peak pulse current flow in the DC link due to faulted dc bus or ground faults during pre-charge operation. The dc link inductor is chosen primarily for cost effective dc bus filtering and ac input power factor steady state considerations. The dc link inductor magnitude can be increase to solve the above mentioned problems but the resulting inductor will be large, costly and dissipate more heat.

Non-linear discontinuous current control algorithm: The non linear discontinuous current control algorithm as shown in Fig. 8 pre-charges the dc-bus capacitor to its peak voltage with fixed dc link inductor and dc-bus capacitor (Gilmore and Skibinski, 1996). This algorithm does not require a current sensor during pre-charging mode to achieve the desirable dc-bus capacitor voltage at fastest possible time by controlling the drive ac input current to the drive steady state current.

The main objective of discontinues current control is to limit the peak dc link current ($I_{link\ (pk)}$) within the converter peak ac line current under steady state operation. This allows the maximum pre-charging current flow from ac line to dc bus capacitor without the nuisance if fuse blowing. The main parameters required for the control are ac to ac line peak voltage (V_m), capacitor dc-bus voltage (V_{bus}) and zero crossing of the line-line voltage. The dc bus capacitor voltage (V_{bus}) is sensed through potential divided and operational amplifier circuit in real time. The V_m is derived for scaled operational amplifier sensed across the ac line voltage with sufficient filtering to reduce the thyristor commutation line notches. The operational amplifier output is further passed through a full bridge precision amplifier and added to form a six pulse rectifier dc value of the peak ac voltage.

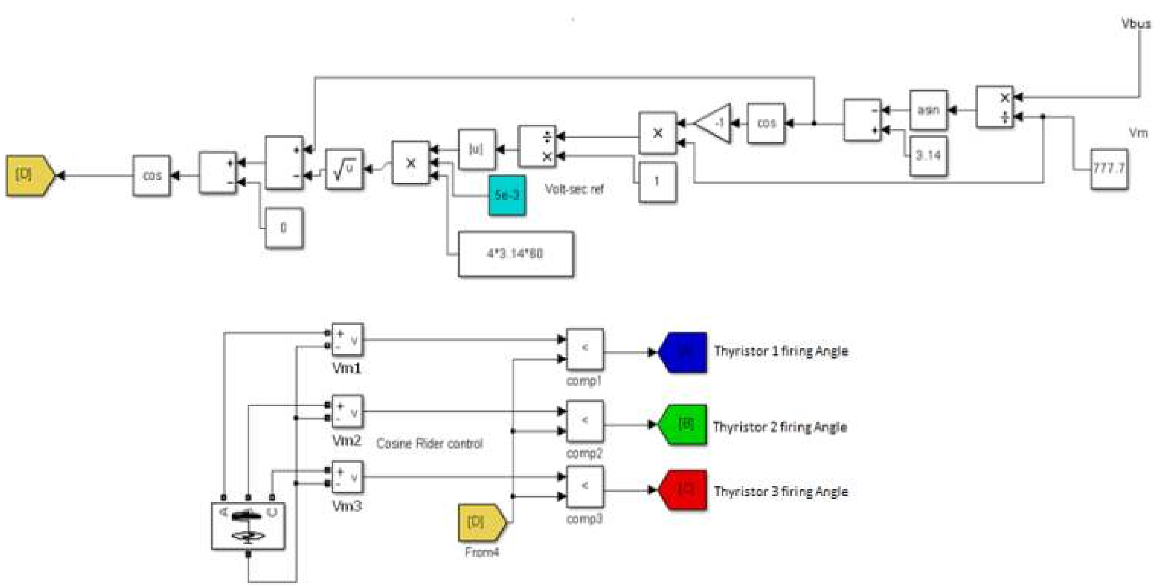

Fig. 8: Non linear discontinuous current control algorithm

The required parameters to find the thyrisistor firing angle is θ_{max}, θ_{min}. where θ_{max} is the operating point angle in radians, correspanding to the intersection of V_m and V_{bus}:

$$E_f = V_m \sin\theta_{\max} \tag{7}$$

where,

$$\theta_{\max}[radians] = \pi - \sin^{-1}\left[\frac{E_f}{V_m}\right] \tag{8}$$

The SCR firing angle (α) (in radians) is calculated from the known θ_{max} and calculated $\Delta\theta_x$. Actual α is calculated by subtracting π/3 from θ_{min} due to the 60° phase shift between α and θ axis:

$$\alpha[radians] = \theta_{\min} - \frac{\pi}{3} \tag{9}$$

where,

$$\theta_{\min} = \theta_{\max} - \Delta\theta_x \text{ (radians)} \tag{10}$$

$$[VS]_R = L_{link} I_{link(pk)} \tag{11}$$

$$\Delta\theta_x[radians] = \sqrt{4\pi f [VS]_R \left(\frac{d\theta}{dV_{ll}}\right)} \tag{12}$$

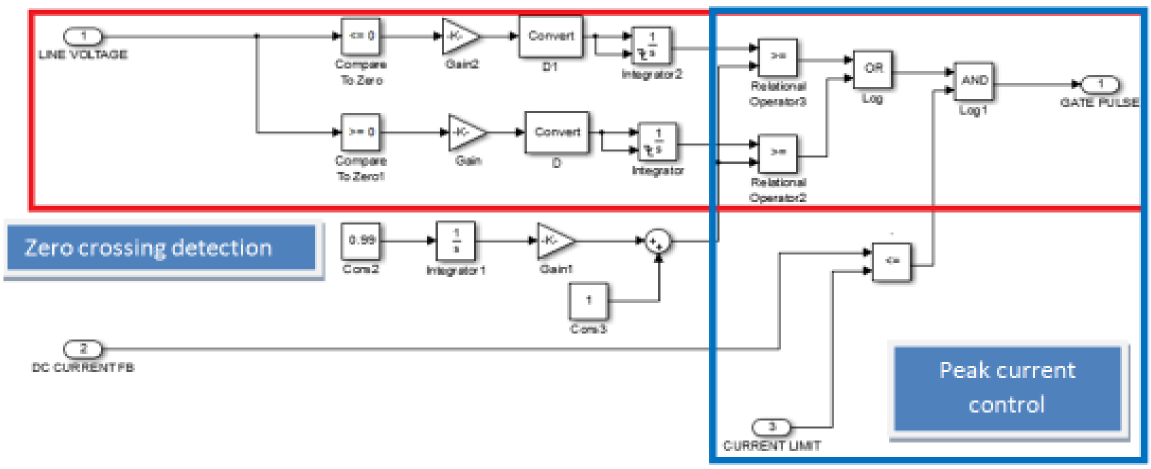

Fig. 9: Proposed soft charging control algorithm (Single phase operation)

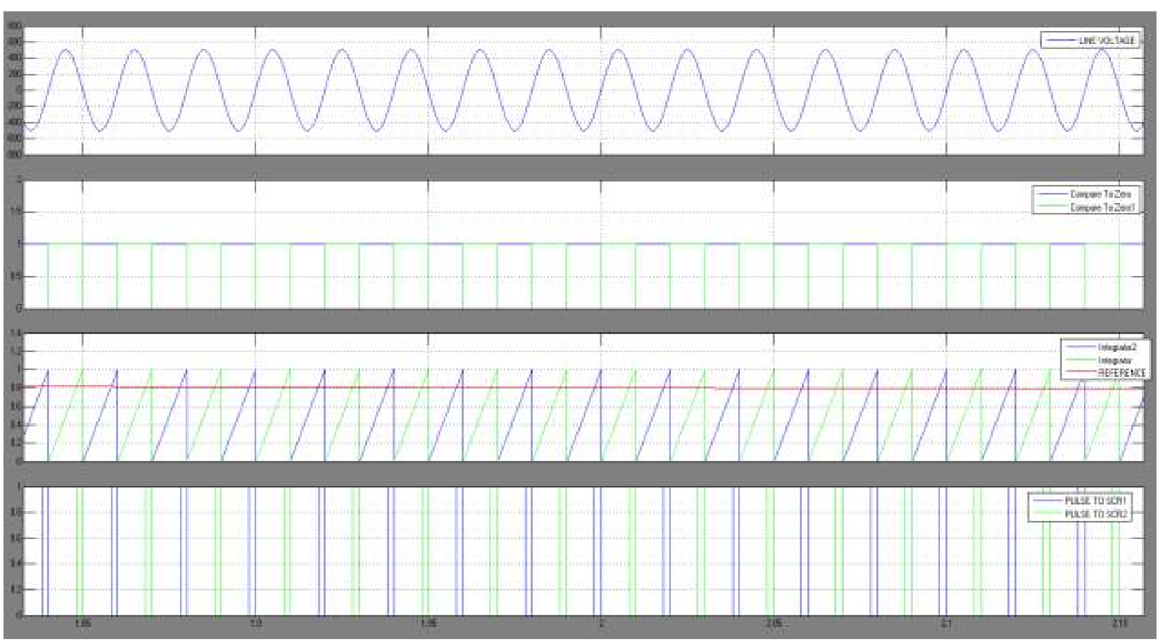

Fig. 10: Waveforms of zero crossing detection for single phase operation

$$\left(\frac{d\theta}{dV_{ll}}\right)_{\theta\max} = ABS\left\{\frac{1}{V_m\{-\cos(\theta_{\max})\}}\right\}[\text{rad/volt}] \quad (13)$$

Non linear discontinuous current control algorithms is robust in operation thereby it can operate into a partially pre-charged bus capacitor and operate with input voltage transients and bus (or) ground faults. Even during bus pre-charging mode the ground (or) bus faults can be sensed and limits the fault current within the rated current to avoid blow of nuisance blow of input fuses.

Proposed current control algorithm: The proposed control algorithm shown in Fig. 9 is for single phase operation consists of two blocks:

- Zero crossing detection
- Peak current mode control

The input line voltage is sensed and compared with a zero crossing detector. The output of the zero crossing detector is a synchronized pulses and the pulses were taken to the integrator and the integrator is reset by the falling edge of the pulses. Thus the output is a synchronized ramp signal. This ramp signal is compared with a reference signal from the controlled integrator which generates the pulses for the switches. The waveform associated with zero crossing detection is shown in Fig. 10. In peak current mode control the DC inductor current is compared with the reference set current and the resultant pulses were compared with the pulses from zero crossing detection and generated the actual gate pulses for IGBT's as shown in Fig. 11.

The above mentioned soft charging control algorithm will be extended for three phase variable frequency drives application. The complete analysis of this control algorithm will be dealt in the next study.

COMPARISON OF DIFFERENT SOFT CHARGING CIRCUITS AND TECHNIQUES

Table 1 different soft charging circuit were compared in all aspects such as cost, volume, controllability, possibility on capacitor soft charging during fault conditions, etc. In resistor-contactor type a high current capability AC/DC contactor and resistor bank were required based on the type of configuration; due to this the cost, volume and power dissipation will be higher. The controllability is easy as there is no controlled switches (or) intelligent circuit were available simple dc-bus capacitor voltage sensing is sufficient, based on the dc-bus capacitor voltage the capacitor charging current flow will be controlled through resistor bank (or) contactor. As there is no intelligent circuit (or) control is available precise control of dc-bus voltage is difficult to achieve and not possible to charge the dc-bus capacitor during bus fault condition. The thyristor switch type also similar to resistor-contactor type soft charging with replacing contactors with thyristors.

In magneto resistance element type the resistor-contactor (or) thyristor switch is replaced by a MR element, the main disadvantage is it can't be used for high power application as the material is not available in the market. In Thyristor Bridge as rectifier the uncontrolled rectifier used in the above mentioned techniques were replaced by thyristor bridge. The thyristors were controlled through preferred control techniques to achieve smooth charging of dc-bus capacitor and without overshoot of dc link current.

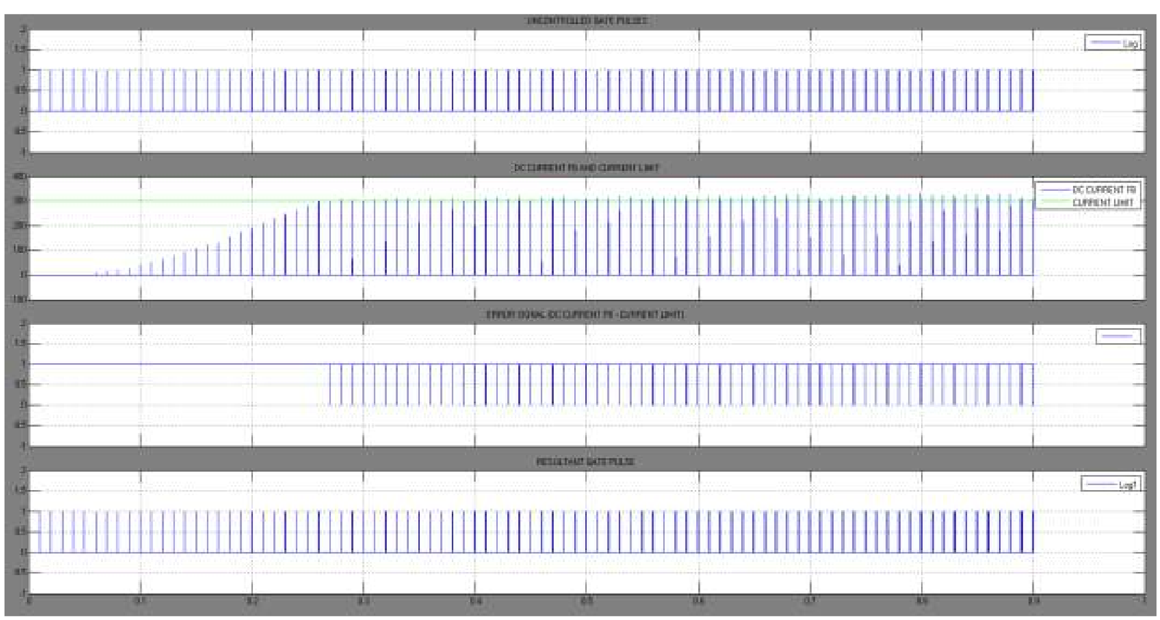

Fig. 11: Waveforms of peak current control for single phase operation

Table 1: Comparison of different soft-charging circuits and techniques

Parameters	Resistor-Contactors	Thyristor switch	Thyristor bridge as rectifier	Magneto resistance element	Proposed three switch buck converter
Cost	High	High	High	High	Low
Volume	High	High	High	High	Low
Power dissipation	High	High	Medium	High	Low
Current sensor requirements	Required	Required	Not required	Required	Simple current sensing is required
Robustness	High	High	Medium	High	High
Controllability	Easy to control but precise control is not possible	Easy to control but precise control is not possible	Separate control algorithm required precision control is possible	Precise control is not possible	Separate control algorithm required precision control is possible
Pre-charging in a partially pre-charged capacitor	Not possible	Not possible	Possible	Not possible	Possible
Pre-charging during ground faults	Not possible	Not possible	Possible	Not possible	Possible
Pre-charging during bus faults	Not possible	Not possible	Possible	Not possible	Possible

The dc-bus capacitor can be charged even during bus fault conditions through sensing of dc-bus voltage and firing the thyristor through back firing technique. In proposed soft charging technique the thyristor bridge is replaced by three switch buck converter where only three controlled switch is required for individual phases. Compared to thyristor bridge rectifier two additional diode will be in the current flow path due to this conduction losses will be little higher. Since there are only three controlled switches the control circuit, technique is very simple and very less control circuit is required. The dc-bus capacitor can be charged during bus fault conditions also through sensing of dc-bus voltage and current flow through the dc link inductor, during bus fault conditions the charging current is limited through current sensing and the dc-bus capacitor is slowly charged to the limit without dc current overshoot through back firing technique.

In linear continuous current control technique the dc link inductor requirement will be higher to have a continuous current and to avoid stress in the switches, peak inductor current due to this inductor cost and volume will be higher. In non linear discontinuous current control technique the inductor value will be limited to reduce the cost and size due to this inductor current will be discontinuous. To avoid the dc peak current the current controlled is implemented through calculating a constant value as per Eq. (11). Through this technique the current sensing circuit can be avoided but the constant value will be based on the soft charging circuit L_{link} *and* I_{link} values. In the proposed current control technique the input line voltage is measured to generate uncontrolled gate pulse which in turn compared with the dc link current to generate the actual gate pulse required of the controlled switches. Through this technique we can limit the dc link current to any value by compromising the dc link capacitor charging time. The difference between non linear discontinuous current control and proposed technique is where the actual current is measured and based on that switches where controlled and the control technique is very simple to implement in low cost microcontroller (or) FPGA.

CONCLUSION

In this study a complete analysis of different soft charging topologies and control techniques were presented, all circuit configurations and control techniques have their own merits and demerits. The Resistor contactor, Thyristor switch and Magneto resistance element type soft charging circuits were older techniques even though they are robust, it's not possible to control the dc link inductor peak current and dc-bus capacitor voltage precisely without overshoot. During brownout condition, ground, bus fault and partially charged capacitors pre-charging of the dc-bus capacitor is not possible as there is no possibility of controlling the input dc inductor current and capacitor charging current.

Thyristor Bridge as rectifier and proposed three switch buck converter type soft charging techniques eliminates the above mentioned demerits. It is possible to control the dc bus capacitor voltage step by step in both the techniques and limit the dc link inductor current within a peak limit with small dc link inductor. The main difference between these two are, three switch buck converter required half the number of controlled switch compared to thyristor bridge rectifier due to this the control board is small, simple control technique, rectifier cost, volume and power dissipation is less. Further research will be continued on using three switch buck converter for soft charging circuits with proposed control technique.

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