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Research Paper

A NEW SINGLE-STAGE MULTILEVEL TYPE FULL-BRIDGE CONVERTER APPLIED TO BRUSHLESS DC MOTOR

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Switch mode rectifiers for power-factor correction have gained considerable attention, due to the increasing demand for improved power quality. A new three-phase single-stage rectifier with Brushless DC motor is proposed in this paper. Each converter operates in the Continuous Conduction Mode (CCM), which allows a high power factor and a small EMI filter. The outstanding features of the proposed rectifier are that it can produce input currents that do not have dead band regions and an output current that can be continuous when the converter is operating from maximum load to at least half of the load. Here we proposed full bridge converter with machine load condition system is validated through MATLAB/SIMULINK Platform.

Keywords: AC-DC power conversion, Single-Stage Power Factor Correction (SSPFC), Three-level converters, DC motor, Brushless DC motor

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INTRODUCTION

Electric power quality is a term which has captured increasing attention in power engineering in the recent years. The measure of power quality depends upon the needs of the equipment that is being supplied. The low power factor and high pulsating current from the AC mains are the main disadvantages of the diode rectifier and phase controlled rectifier. A three phase ac-dc power conversion with input Power Factor Correction (PFC) and transformer isolation is typically done using a six-switch front-end ac-dc converter to do the PFC and a four-switch full-bridge converter to do the dc-dc conversion (Ziogas *et al.*, 1985).

This approach, however, is expensive and complicated as it needs ten active switches along with associated gate drive and control circuitry. Moreover, the converter must be operated with sophisticated control methods

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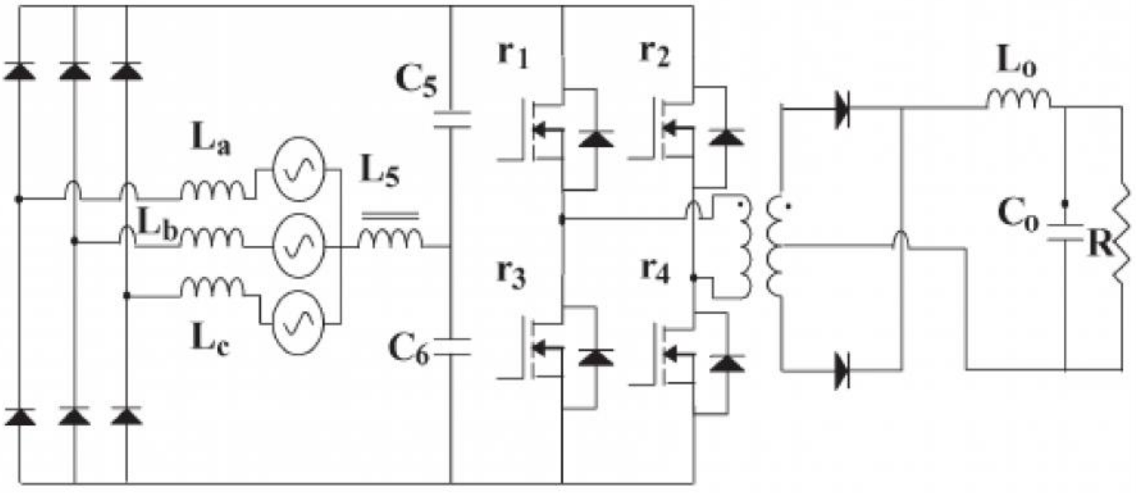
that require the sensing of certain key parameters such as the input currents and voltages; this is particularly true if online Pulse Width Modulation (PWM) techniques are used. Researchers have tried to reduce the cost and complexity of the standard converter by modifying the ac-dc front end converters. Proposed alternatives have included: 1) using three separate ac-dc boost converter modules (Spiazzi and Lee, 1997); 2) using a reduced switch ac-dc converter (Lin and Wu, 1998); and 3) using a single-switch boost converter (Prasad *et al.*, 1989). Two separate switch-mode converters are still needed, however, to perform three-phase ac-dc power conversion with transformer isolation. Researchers have tried to further reduce the cost and complexity associated with single-phase and three-phase ac-dc power conversion and PFC by proposing single-stage converters that integrate the functions of PFC and isolated dc-dc conversion in a single power converter. Previously proposed three-phase single-stage ac-dc converters as shown in Figure 1, however, have at least one of the following drawbacks that have limited their widespread use.

- They are implemented with three separate ac-dc single stage modules.
- Converter components are exposed to very dc bus high voltages so that switches and bulk capacitors with very high voltage ratings are required.
- Input currents are distorted and contain a significant amount of low-frequency harmonics because the converter has difficulty performing PFC and dc-dc conversion simultaneously.
- Converter must be controlled using very sophisticated techniques and/or non-standard techniques. This is particularly of resonant type converter that need variable switching frequency control methods to operate.
- Output inductor must be very low, which makes the output current to be discontinuous. This results in a very high output ripple so that secondary diodes with

Figure 1: Previous Proposed AC/DC Single Stage Converter



high peak current ratings and large output capacitors to filter the ripple are needed. This paper presents a new three-phase, single-stage rectifier that does not have any of these drawbacks. In this paper, the operation of the new converter is explained, its features and design are discussed in results, and converter is applied to drive to check the performance of drive.

CONVERTER OPERATING PRINCIPLE

The proposed converter and its key waveforms are shown in Figures 2 and 3. The basic principle behind the proposed converter is that it used auxiliary windings that are taken from the converter transformer to cancel the dc bus capacitor voltage so that the voltage that appears across the diode bridge output is zero. This voltage cancellation occurs whenever there is voltage across the main transformer winding and current in the input inductors rises when it does. When there is no voltage across the main transformer primary winding, the total voltage across the dc bus capacitors appears at the output of the diode bridge; since this voltage is greater than the input voltage, the input currents falls.

Figure 2: Newly Proposed AC/DC Single Stage Converter

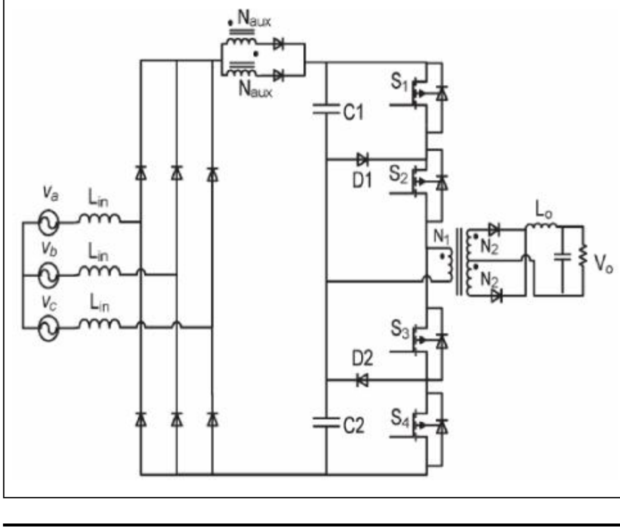
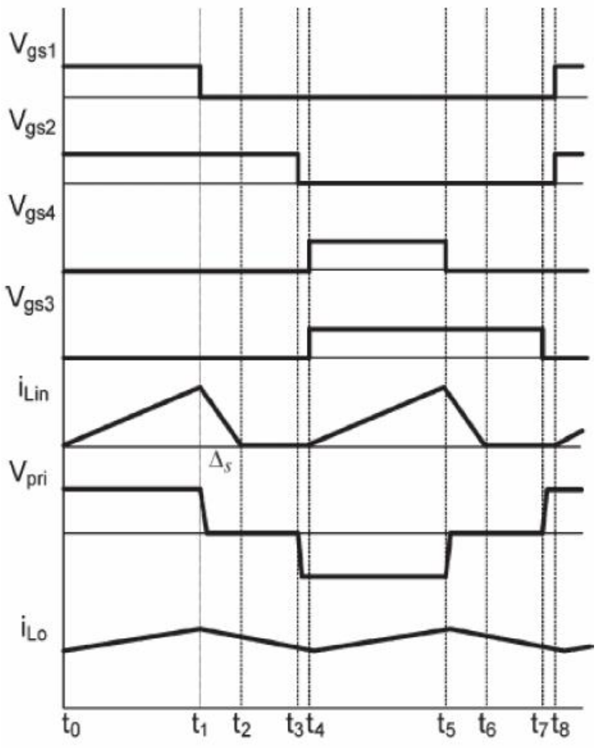


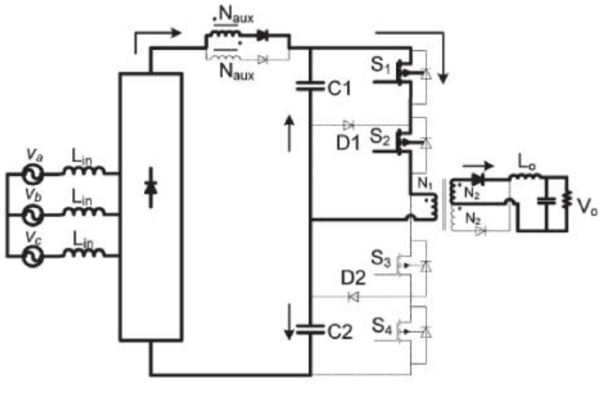
Figure 3: Typical Waveforms Describing the Modes of Operation



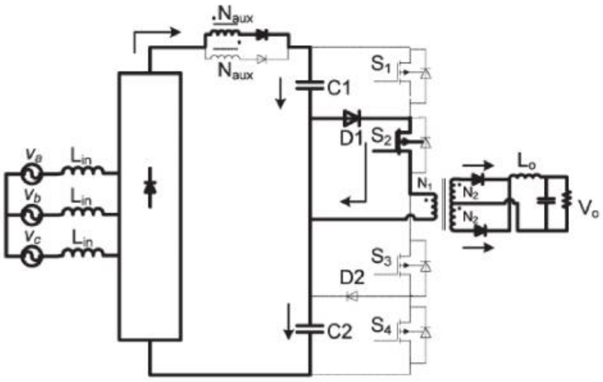
To simplify the analysis, the following assumptions are made, If the input currents are discontinuous, they will be naturally nearly sinusoidal (when filtered) and in phase with the input voltages.

- The input voltage value can be considered as constant within a switching period as the period of the three-phase voltage supply is much longer than the switching period;
- All devices are ideal;
- The currents in inductors *La* = *Lb* = *Lc* = *Lin* are *iLa*, *iLb*, *iLc* and have the same amplitude;
- The *dc* bus voltage has no ripple.

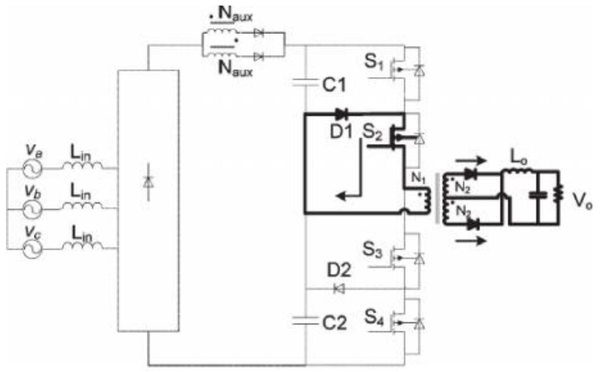
Figure 4: Modes of Operation



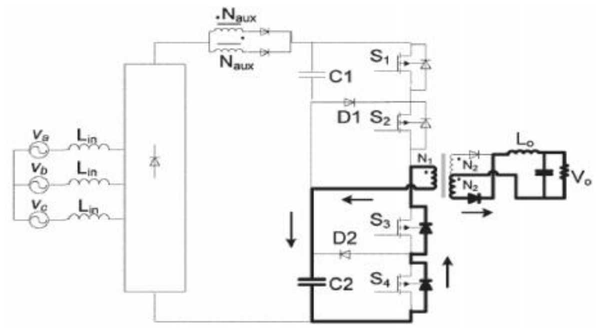
(a) Mode 1(*t*0 < *t* < *t*1)



(b) Mode 2 (*t*1 < *t* < *t*2)



(c) Mode 3 (*t*2 < *t* < *t*3)



(d) Mode 4 (*t*3 < *t* < *t*4)

The equivalent circuit in each stage is shown in Figure 4. The converter goes through the following modes of operation in a half switching cycle.

Mode 1 (*t*0 < *t* < *t*1)

During this interval, switches *S*1 and *S*2 are ON. The switches remain ON for a period given by *D*/2*fsw*. In this mode, energy from the dc link capacitor *C*1 flows to the output load. Due to magnetic coupling, a voltage appears across one of the auxiliary windings and cancels the total dc bus capacitor voltage; the voltage at the diode bridge output is zero, and the input currents rise. Due to the high switching frequency, the supply voltage is assumed constant within a switching cycle. In this mode, the three-phase input current equations are as follows:

$$3_a = L_a \frac{di_{La}}{dt}$$

$$3_b = L_b \frac{di_{Lb}}{dt}$$

$$3_c = L_c \frac{di_{Lc}}{dt}$$

$$i_{La} + i_{Lb} + i_{Lc} = 0$$

$$3_a + 3_b + 3_c = 0 \qquad \text{...(1)}$$

As it can be seen from (1), the equations that describe the relation between the current and voltage of input currents *iLa*, *iLb*, and *iLc* are the same, but with different notation. Therefore, instead of using terms with subscripts *a*, *b*, and *c* in this paper, a general notation $\rightarrow$ is defined so that only one equation is written instead of three equations. Equation (1) can thus be rewritten as

$$\vec{3} = L_{in} \frac{d\overrightarrow{\S_{L_{in}}}}{dt} \qquad \text{...(2)}$$

The auxiliary inductor current increases during this mode, and the following expression can be written:

$$\overrightarrow{\S_{L_{in}},k}(t) = \frac{\left|\overrightarrow{^{3}{}_{k}}\right|}{L_{in}} \cdot t \cdot \qquad \text{...(3)}$$

At the end of Mode I, the current in the auxiliary inductor L_{in}, during the k^{th} interval is

$$\vec{\S}_{L_{in}} k,\ \text{max} = \frac{\left|\overrightarrow{^{3}k}\right|}{L_{in}} \cdot \frac{D}{2f_{sw}} \qquad \text{...(4)}$$

where ${}^{3}k$ is the average value of the supply voltage in the interval k, D is the duty cycle, and fsw is the switching frequency. Since the converter operates with a steady-state duty cycle D that is constant throughout the line cycle, the peak value of an input inductor current at the end of this mode is dependent only on the supply voltage.

The output inductor current can be expressed as

$$i_{L_o}(t) = \frac{\frac{V_{bus}}{2N} - V_L}{L_o} \cdot t \qquad \text{...(5)}$$

where V_{bus} is the average dc-link voltage and VL is the average load voltage and N is the transformer ratio between input and output ($N = n1/n2$). If it is assumed that the output inductor current is continuous, then the following expression for peak to peak ripple can be derived:

$$\Delta i_{L_o} = \frac{\frac{V_{bus}}{2N} - V_L}{L_o} \cdot \frac{D}{2f_{sw}} \qquad \text{...(6)}$$

Mode 2 ($t1 < t < t2$)

In this mode, $S1$ is OFF, and $S2$ remains ON. The energy stored in the auxiliary inductor during the previous mode is completely transferred into the dc link capacitor. The amount of stored energy in the auxiliary inductor depends upon the rectified supply voltage. This mode ends when the auxiliary inductor current reaches zero. Also, during this mode, the load inductor current freewheels in the secondary of the transformer. The voltage across the auxiliary inductors in Mode II is $Vk| - V_{bus}$, thus, the auxiliary current expression is as follows:

$$\frac{d\overrightarrow{\S_{L_{in}}}}{dt} = \frac{\left|\vec{V}_k\right| - V_{bus}}{L_{in}}$$

$$\vec{\S}_{L_{in}},\ k(t) = i_{L_{in}},\ k,\ \text{max} - \frac{V_{bus} - \left|\vec{V}_k\right|}{L_{in}} \cdot t \cdot \qquad \text{...(7)}$$

This mode ends when the auxiliary inductor current reaches zero. This mode lasts for $\Delta s,k/2fsw$ amount of time; using (4), the following expression can be found:

$$\vec{\Delta}_{s,k} = \frac{\left|\vec{V}_k\right|}{V_{bus} - \left|\vec{V}_k\right|} D \qquad \text{...(8)}$$

where $\Delta s, k$ is the normalized period of Mode II. Equation (8) shows that the duration of this mode is time varying along one ac line period. In order to ensure a discontinuous input current, the normalized period $\Delta s, k$ must satisfy the expression $D + \Delta s, k < 1$ for any interval k and any load conditions. Using (8), this constraint can be written as:

$$V_{bus} > \frac{\left|\vec{V}_k\right|}{1 - D} \qquad \text{...(9)}$$

On the other hand, the load inductor current freewheels in the secondary of the transformer, which defines a voltage across the load filter inductor equal to $-VL$; therefore, the load inductor current is given by

$$i_{L_o}(t) = i_{L_o\max} - \frac{V_L}{L_o}t \qquad ...(10)$$

$$\Delta i_{L_o} = \frac{V_L}{L_o}\frac{1-D}{2f_{sw}} \qquad ...(11)$$

Consequently, the following expression can be derived from (6) and (11)

$$V_o = \frac{V_{bus}}{2N}D \qquad ...(12)$$

Mode 3 ($t2 < t < t3$)

In this mode, the primary current of the main transformer circulates through $D1$ and $S2$, and the output inductor current freewheels in the secondary. There is no energy transferred to the dc bus capacitors.

Mode 4 ($t3 < t < t4$)

In this mode, $S1$ and $S2$ are OFF, and the primary current of the transformer charges $C2$ through the body diodes of $S3$ and $S4$. Switches $S3$ and $S4$ are switched ON at the end of this mode and the half switching cycle ends. For the remainder of the switching cycle, the converter goes through Modes 1 to 4, but with $S3$ and $S4$ ON instead of $S1$ and $S2$.

Mode 5 ($t4 < t < t5$)

In this mode, $S3$ and $S4$ are ON; a symmetrical period begins. In this mode, energy flows from the capacitor $C2$ into the load. The voltage across the auxiliary inductors becomes only the rectified supply voltage of each phase, and the current flowing through each inductor increases.

Mode 6 ($t5 < t < t6$)

In this mode, $S3$ is ON, and S4 is OFF. The energy stored in the auxiliary inductors during the previous mode is completely transferred into the dc-link capacitor.

Mode 7 ($t6 < t < t7$)

In this mode, $S4$ is OFF, and the primary current of the main transformer circulates through the diode $D2$ and $S3$. The output inductor current also freewheels in the secondary of the transformer during this mode.

Mode 8 ($t7 < t < t8$)

In this mode, $S3$ and $S4$ are OFF, and the primary current of the transformer charges the capacitor $C1$ through the body diodes of $S1$ and $S2$. Switches $S1$ and $S2$ are switched on at the end of this mode. Output voltage regulation can be done by standard control methods that control duty cycle D. Duty cycle, D in (4), is defined as the time when $S1$ and $S2$ are both ON during the first half cycle or when $S3$ and $S4$ are both ON during the second half cycle. These two cases correspond to energy transfer modes of operation. Any control method that can be used to regulate a two-level full-bridge converter by controlling D can be used to regulate the proposed converter; the only difference is how the gating signals are implemented. For example, the control for the proposed converter can be implemented with a conventional phase-shift PWM controller, and some logic can be added to the output of the controller to generate the appropriate gating signals. Since the converter is a multilevel converter, it should be implemented with some sort of capacitor voltage balancing to ensure the voltage across each bus capacitor is the same.

Various such techniques have been proposed in the literature, including techniques that sense the capacitor voltages and adjust the duty cycle of the converter switches appropriately.

MATLAB/SIMULINK MODELLING AND SIMULATION RESULTS

Here the simulation is carried out by two cases:

- Proposed Full Bridge Multilevel Converter.
- Proposed Full Bridge Multilevel Converter with DC Machine Loading.

Case 1: Proposed Full Bridge Multilevel Converter

As above Figure 5 shows the Matlab/ Simulink Model of Proposed Multilevel Full Bridge Converter.

As above Figure 6 shows the input current and voltage, it represents the source side power factor of proposed converter.

As above Figure 8 shows the voltage across the switch in proposed multilevel full bridge converter.

As above Figure 9 shows the Output Voltage of Proposed Multilevel Full Bridge Converter. Here we get output at steady state after the 0.1 sec.

Figure 5: Matlab/Simulink Model of Proposed Multilevel Full Bridge Converter

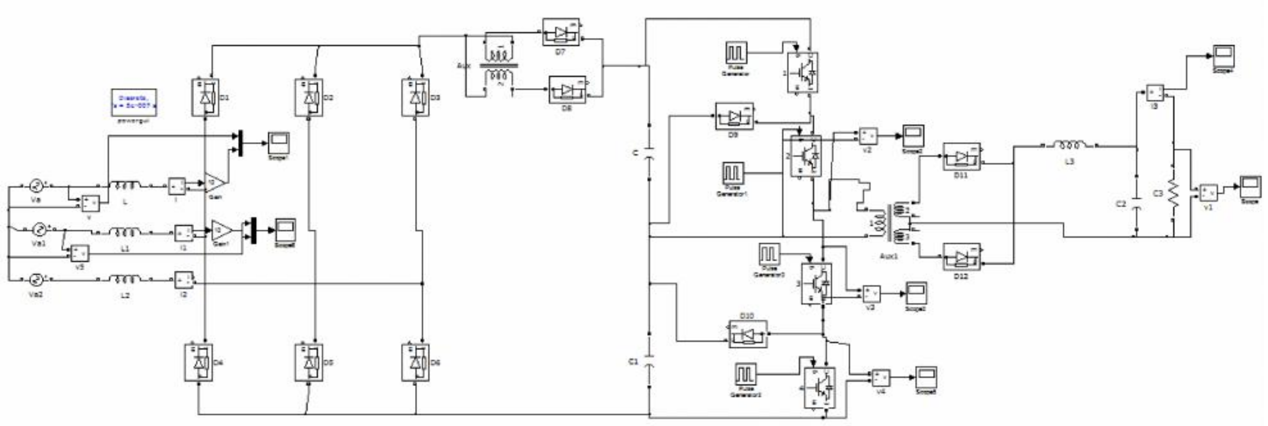


Figure 6: Input Current and Voltage

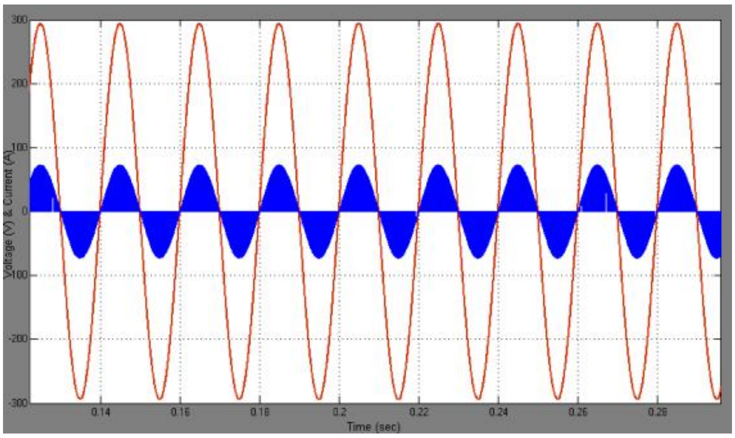


Figure 7: Voltage at Primary Side Transformer

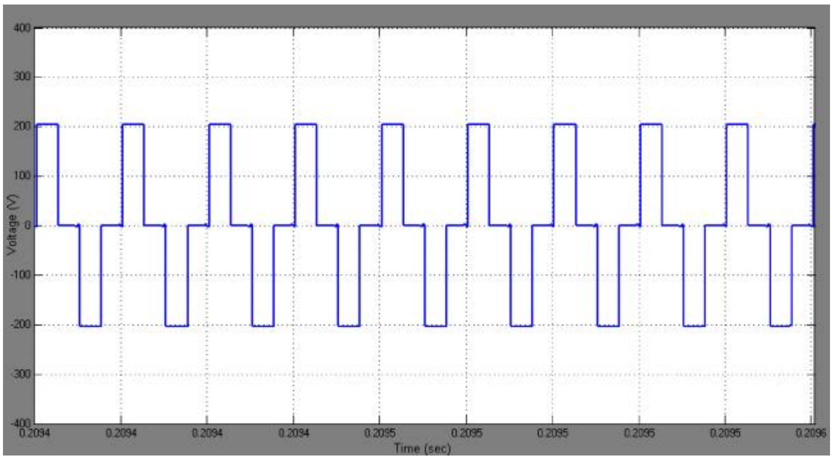


Figure 8: Voltage Across Switch

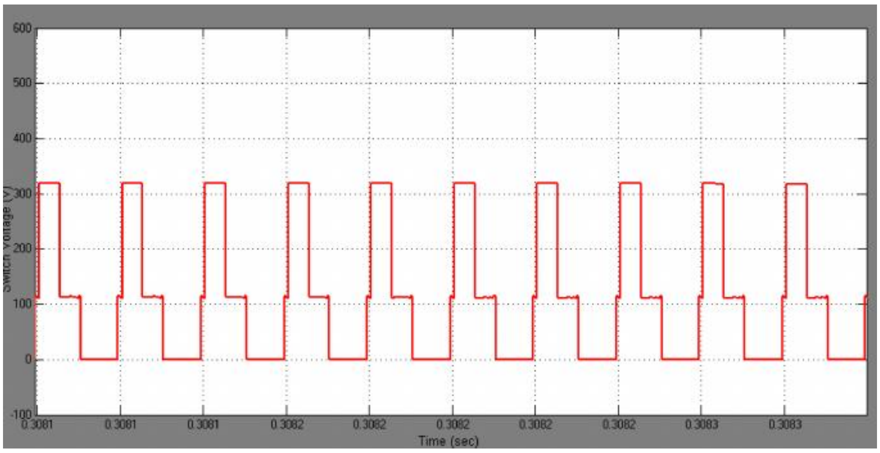


Figure 9: Output Voltage

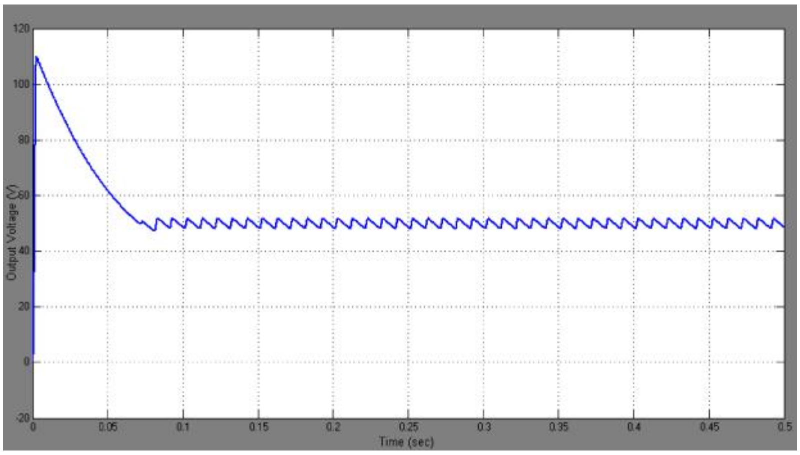


Figure 10: Matlab / Simulink Model of Proposed Multilevel Full Bridge Converter with Machine load

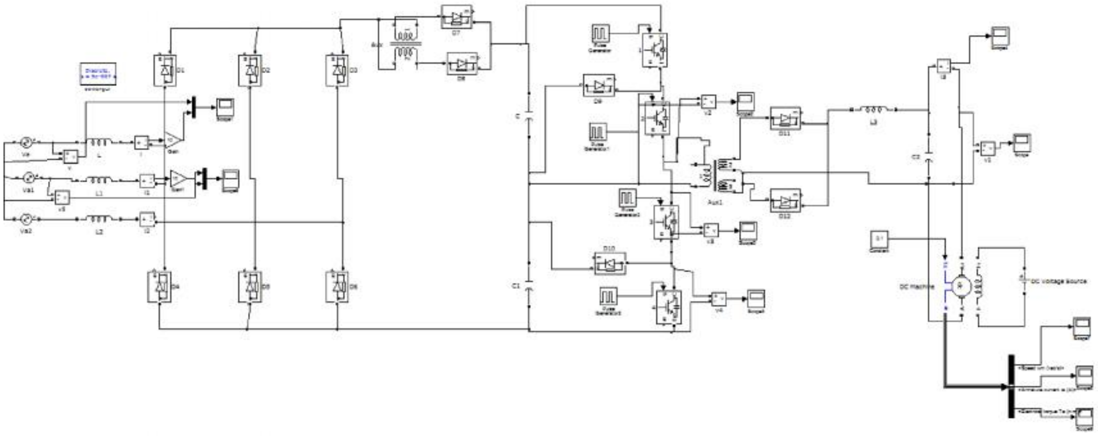


Figure 11: Speed of Motor

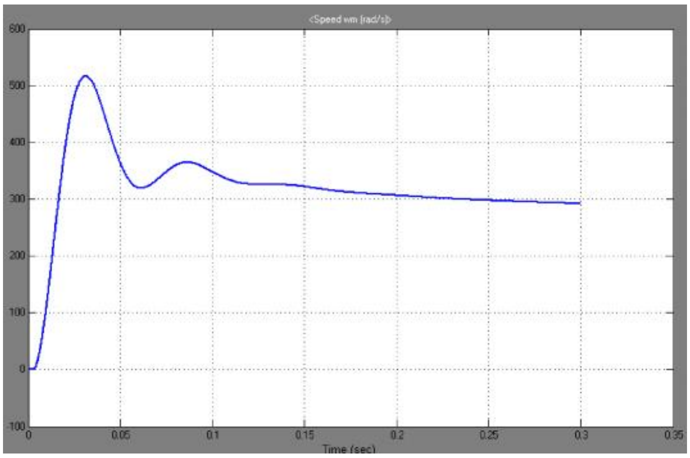


Figure 12: Armature Current

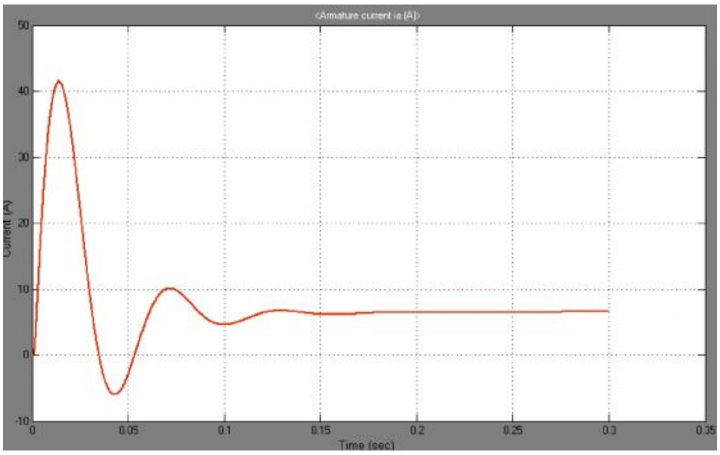


Figure 13: Electromagnetic Torque

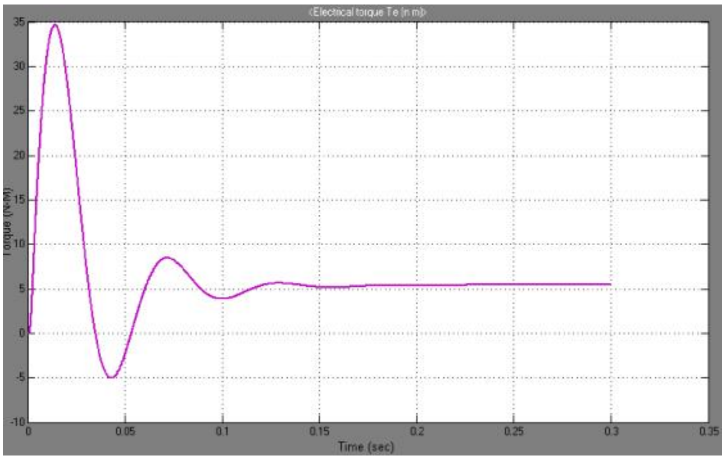


Figure 14: Matlab/Simulink Model of Proposed Multilevel Full Bridge Converter with Brushless dc Machine Load

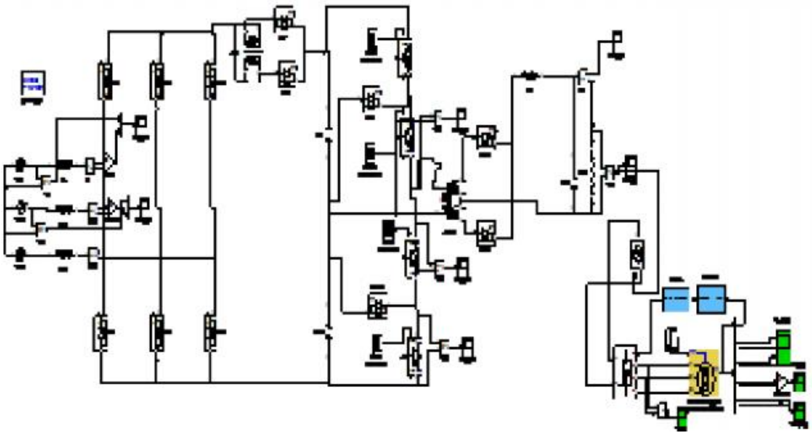


Figure 15: A) Stator Current (Ia), B) Electromotive Force (Ea)

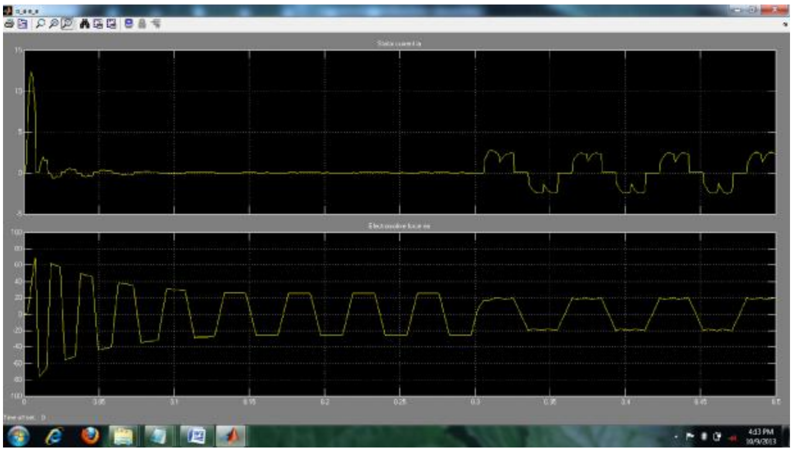


Figure 16: Rotor Speed (rpm)

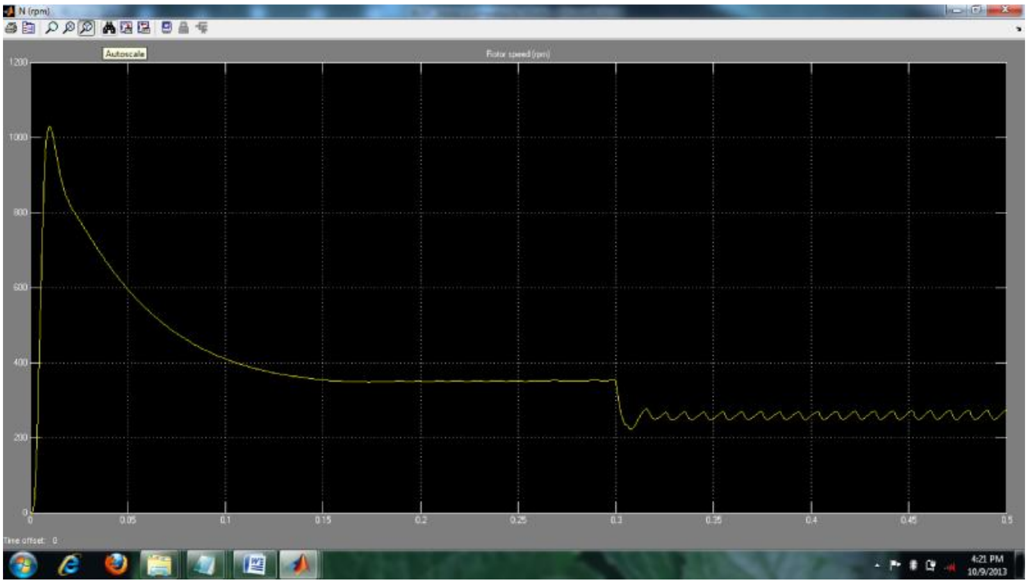
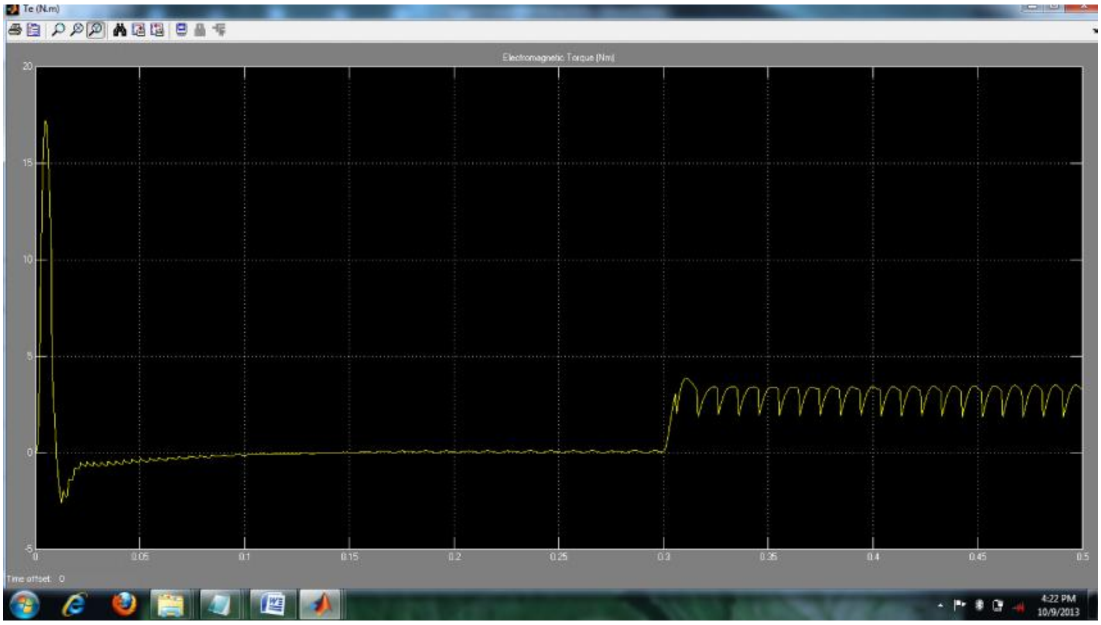


Figure 17: Electomagnetic Torque (Nm)



Case 2: Proposed Full Bridge Multilevel Converter with Machine Loading

As above Figure 10 shows the Matlab/ Simulink Model of Proposed Multilevel Full Bridge Converter with DC machine loading.

As figure shows the performance characteristics of DC motor with proposed multilevel full bridge converter.

As above Figure 14 shows the Matlab/ Simulink Model of Proposed Multilevel Full

Bridge Converter with Brushless DC machine loading.

CONCLUSION

A three-phase, three-level, single-stage power-factor corrected ac/dc converter that operates with a single controller to regulate the output voltage was presented in this paper. The proposed converter has the following features. Proposed converter has an auxiliary circuit that can cancel the capacitor voltage in which way the input inductor acts as a boost inductor to have a single-stage PFC. Proposed converter can operate with lower peak voltage stresses across the switches and the dc bus capacitors as it is a three-level converter. This allows for greater flexibility in the design of the converter and ultimately improved performance, proposed converter is applied to Brush less dc machine to check the machine performance.

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