Fuzzy controller based power quality improvement in three level converter with multiloop interleaved control for marine AC/DC applications

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This integration of PI controller (voltage) and fuzzy controller (current) in multiloop interleaved control (MIC) operated three level converter for marine AC/DC applications is proposed. Parameters characterizing the power quality comprise Total Harmonic Distortion (THD) and input power factor are measured along with steady state and dynamic performance analysis in single phase three level AC-DC converter which is simulated in MATLAB/Simulink. MIC’s merits are reduction of compensating block and number of parameter sensing still individual capacitor voltages can be balanced. This system possesses PI as external twirl voltage controller and internal twirl current controller integrated in MIC where the current controller is now replaced as FLC. From the simulation results, it is found that FLC current controller with PI voltage controller performs better with 3.23% of source current THD at rated power and less than 5% for wide load variations and affirms unity power factor compared to conventional PI controller.

[Keywords: MIC, FLC, PI, Power Factor (PF), Total Harmonic Distortion (THD), three-level boost converter]

Introduction

Single-phase AC-DC converters are very commonly preferred as front end rectifiers for marine applications because of its high power density and increased efficiency. Typical diode/thyristor rectifiers yield poor power factor and inject high harmonics into source current thus pollute the power quality of input ac mains. Inserting an inductor on the AC supply side to improve a current waveform but this reduces the power factor 1-3. Permissible limits of harmonics in supply current is prescribed by IEEE 519 and IEC 1000-3-2 4,5, the Power Factor Correction (PFC) is given more attention nowadays due to the evolution and tremendous usage of power-electronic products. Boost type converters are chiefly employed in power factor correction as it works with continuous source current and the magnitude of dc voltage is surely larger than source voltage’s maximum value 6. The term multiloop refers to outer voltage loop comprising of PI controller and an inner current loop where PI and fuzzy controllers are employed. The regulated dc output voltage and boost inductor current are sensed; both the signals are applied to the corresponding loops, got processed by controllers and produce desired gating pulses to the converter to ensure proper function ⁷-¹⁰.

In ¹¹ and ¹², extra compensation blocks are integrated in multiloop control for motor applications enhance power quality at supply side. Power switch of single component has to bear the whole regulated dc output at the time of blocking period of MOSFET. When employed in high power applications, power devices are subjected to severe voltage stress. Usage of multilevel converters is the best solution for the above mentioned problems when operated in high power/voltage applications. Classical three-level converter comprises eight power switches which is the major limitation of the topology. Hence, three level AC-DC converter with two power semiconductor switches is presented in this paper.

In high power applications, single level boost converter needs bulk inductance, and provides high current distortion. In order to reduce bulk inductance, to reduce the electromagnetic interference (EMI), multilevel converters comprising low potential pressure
devices are found to be suitable in high voltage working environment. Capacitors are cascaded to the switches for production of three levels of output voltage in multilevel boost topology. Thus, voltage stress to each switch is reduced to half the amount as compared to boost converter. Therefore, lesser current ripples in boost three-level rectifier in comparison to classical boost converter. DC/DC conversion is involved in fuel cell applications and grid-integrated applications are the areas where three level converters are chiefly employed.

Power switches able to withstand high voltage stress possess larger drain-source resistances. Lesser ripple current, low switching stress and low switching loss are the merits of three-level converter. DC-DC three-level converter is integrated with bridge rectifier forms three-level AC-DC converter. Gating pulses to three-level SMR (ac/dc application) are generated using lookup table. Individual capacitor voltage sensing and extra voltage compensation sub-blocks must be included for proper functioning of multilevel converter in dc/dc applications.

The nominal characteristic of AC-DC multilevel converter with interleaved PWM control is derived. The result of interleaved PWM three level AC-DC rectifier behaves similar to conventional AC-DC boost converter even when the two dc-link capacitor voltages are imbalanced. Interleaved PWM control signals obtained from multiloop control doesn’t require region selector and supplementary compensation blocks. Also, less volume of inductance is used in multilevel boost configuration circuit. Hence, MIC is more feasible than the typical control method. PI voltage and PI current control technique adopted in, claimed to have achieved 4.43% THD in source current and 0.994 input power factor. Recently, Fuzzy intelligent controller is implemented for control signals generation. In FLC is used in DC-DC converter and also used in two level AC-DC converter.

In this paper, fuzzy logic current control is proposed in multiloop interleaved control without feed forward loop for the single-phase boost type AC-DC three-level rectifier for marine applications. The incorporation of attaining source side low THD and unity PF with the help of PI (voltage) – PI (current); PI (voltage) – Fuzzy (current) control strategies are implemented. The results obtained for FLC based current supervisor are correlated with the results obtained for classical PI current supervisor. The novel PI-fuzzy combination integrated with multilevel boost topology finds its applications in marine areas like front stage for battery charger, UPS, and three-level inverter related applications. This manuscript suggested improved fuzzy logic current controller with PI voltage control method. In this work, source current Total Harmonic Distortion of 3.23% was achieved and also power factor closer to unity which is better than that reported in literature. Also the supply current THD attained is within the IEEE-519 specifications.

Materials and Methods

Figure 1 presents the dual boost type converter circuit for marine applications. An inductor $L_2$ is used to reduce current ripple. Four possible modes of operation exist in correspondence to the ON/OFF positions of two power MOSFETs $(S_1, S_2)$.

The capacitor voltage and inductor current equations during ON state of both the MOSFETs $(S_1, S_2)$ are

\[ v_C = L_i \frac{di}{dt} \quad (i) \]

\[ C_1 \frac{dv_C}{dt} = -\frac{v_C}{R} \quad (ii) \]

\[ C_2 \frac{dv_C}{dt} = -\frac{v_C}{R} \quad (iii) \]

Similarly during $S_1$-ON & $S_2$-OFF

\[ L_2 \frac{di}{dt} = v_i - \frac{v_C}{2} \quad (iv) \]

\[ C_i \frac{dv}{dt} = -\frac{v}{R} \quad (v) \]
\[ C_1 \frac{dv_1}{dt} = i_1 - \frac{v_s}{R} \]  

Correspondingly for the condition during \( S_1\text{-OFF} \) and \( S_2\text{-ON} \) 
\[ L_s \frac{di}{dt} = v_s - v_o \]  

\[ C_1 \frac{dv_1}{dt} = i_1 - \frac{v_s}{R} \]  

\[ C_2 \frac{dv_2}{dt} = -\frac{v_u}{R} \]  

Finally, during both MOSFETs \((S_1, S_2)\) in OFF state 
\[ L_s \frac{di}{dt} = v_s - v_o \]  

\[ C_1 \frac{dv_1}{dt} = i_1 - \frac{v_s}{R} \]  

\[ C_2 \frac{dv_2}{dt} = -\frac{v_u}{R} \]  

The derived transfer function for three level converter is given by, 
\[ \frac{V_o(s)}{d(s)} = \frac{v_o (1-D)}{s L_b C + \frac{2L_b}{R} + (1-D)^2} \]  

Design Equations

Boost Inductor,  
\[ L_b = \frac{V_o}{4f_s \Delta I} \]  

where,  
\( V_o \) - regulated dc voltage  
\( \Delta I \) - boost inductor ripple current  
\( f_s \) - MOSFETs \((S_1, S_2)\) frequency

DC Link Capacitor,  
\[ C_1 = C_2 = \frac{L_b}{2 \omega \Delta V_1} \]  

where,  
\( \Delta V_1 \) - capacitor ripple voltage  
\( \omega \) - angular frequency \((\text{input voltage})\)  
\( I_o \) - output dc current \((\text{dc current})\)

Applying the values of Table 1 to the equation (1), we get  
\[ \frac{V_o(s)}{d(s)} = \frac{32.16 - 11.1 \times 10^{-3} s}{2.1 \times 10^{-3} s^2 + 0.13 \times 10^{-3} s + 0.4489} \]  

Table 1. Design specifications and circuit parameters

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input line voltage ( (V_s) )</td>
<td>28 V</td>
</tr>
<tr>
<td>2</td>
<td>Output voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>3</td>
<td>Output power</td>
<td>100 W</td>
</tr>
<tr>
<td>4</td>
<td>Switching frequency ( (f_s) )</td>
<td>10 kHz</td>
</tr>
<tr>
<td>5</td>
<td>Duty cycle ( (D) )</td>
<td>0.33</td>
</tr>
<tr>
<td>6</td>
<td>Line frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>7</td>
<td>Boost inductor ( (L_b) )</td>
<td>3 mH</td>
</tr>
<tr>
<td>8</td>
<td>Capacitance ( C_1=C_2 )</td>
<td>7000 ( \mu ) F</td>
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<tr>
<td>9</td>
<td>Load resistance</td>
<td>23 ( \Omega )</td>
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</table>

Figure 2 shows the multi loop interleaved control \((\text{MIC})\) block of the boost type three level AC-DC converter for marine applications. It comprises of phase locked loop, conventional multi loop control with voltage controller and current controller, feed forward loop and interleaved PWM scheme. Output voltage is sensed and compared with actual reference in order to produce error voltage which is then processed by voltage controller.
The multiloop interleaved control can be reduced with the exclusion of feed forward loop. This reduced multiloop interleaved control is accompanied with fuzzy logic current controller provides the same tracking performance without the necessity of feed forward loop. The proposed control circuit is shown in Figure.3. The PI controller minimizes the error value at most to zero. Rise time got reduced by tuning proportional gain ($K_p$) and steady state error got vanished by tuning integral gain ($K_i$) helps three level converter to produce desired output.

![Fig. 3. Proposed block diagram of control circuit](image)

Error in output voltage after got processed by the PI controller provides the maximum value of supply current. 0.3 and 3.4 are the corresponding values of $K_p$ and $K_i$ respectively. With these gain constants, PI controller regulate the output voltage to predefined set value.

Deviating nature of the three level converter while put into operation under time varying conditions can be handled by the intelligent FLC. Here, FLC is chosen as current controller. FLC is fed with inductor error current. Design of fuzzy logic controller is illustrated in Figure 3a, 3b and 3c. The very liable mandani fis structure is employed.

![Fig. 3a. Membership functions for the input 1 (error current)](image)

![Fig. 3b. Membership functions for the input 2 (derivative error current)](image)

![Fig. 3c. Membership functions for the output (control signal)](image)

Table 2 depicts the rules formed for proper operation of FLC. Error current and derivative error current are the input variables; controlled output signal is the output variable involved in FLC design.

<table>
<thead>
<tr>
<th>CE</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
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<td>E</td>
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<td>NM</td>
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</table>

NB- NegativeBig, NM-Negative Medium, NS-Negative Small, Z-Zero, PS-Positive Small, PM- Positive Medium, PB-Positive Big.
Figure 4a presents the simulink model of three level boost type AC-DC converter integrated with multiloop interleaved control for marine applications. Simulation was executed in MATLAB. Here, PI (voltage)-Fuzzy (current) controller combination is implemented for regulating dc voltage and shaping of supply current in three level boost type switched mode rectifier. By implementing this controllers combination, the desired power factor correction (i.e.) unity power factor, lesser THD in source current can be achieved in addition to the output voltage regulation. And the feed forward loop can be eliminated by implementing fuzzy logic current control. Thus the desired power factor correction can be achieved by using multiloop interleaved control with the reduction in feed forward loop.

Figure 4b shows the simulink model representing three level AC-DC converter with PI-PI (voltage-current) control. The PI controller with MIC control loop implemented in MATLAB/SIMULINK takes care of the steady state error caused in the system. The output voltage is regulated and THD value obtained is 4.16%. Figure 4c shows simulink model representing three level AC-DC converter with PI-Fuzzy (voltage-current) control.

Results and Discussions

Figure 5a shows the supply side voltage/current signals for proportional integral control. Zero phase shift is maintained by both voltage & current signals providing unity power factor. The output voltage is regulated at 48V. Figure 5b shows the FFT analysis of source current using PI-PI (voltage-current) controller at nominal load. From the FFT analysis, source current distortion obtained is 4.16% which is within the IEEE standard value of less than 5%.

Table 3 indicates the behaviour of three level boost type AC-DC converter under load variations. At rated load condition, THD of supply current is 4.16%. The input power factor becomes 0.9991 (i.e.) nearly unity. By increasing the load resistance, source current harmonics also increases and output voltage is maintained constant.
load variations with THD less than 5% and PF approaches to unity.

<table>
<thead>
<tr>
<th>Percentag e of Load (%)</th>
<th>Output Voltage (V)</th>
<th>Source Current THD (%)</th>
<th>Input Power Factor</th>
<th>Efficiency (%)</th>
</tr>
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<tr>
<td>100</td>
<td>48</td>
<td>3.23</td>
<td>0.9998</td>
<td>90.65</td>
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<tr>
<td>75</td>
<td>48</td>
<td>2.65</td>
<td>0.9997</td>
<td>90.49</td>
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<tr>
<td>50</td>
<td>48</td>
<td>2.37</td>
<td>0.9996</td>
<td>89.93</td>
</tr>
<tr>
<td>25</td>
<td>48</td>
<td>3.10</td>
<td>0.9993</td>
<td>89.89</td>
</tr>
</tbody>
</table>

Table 4 shows the behaviour of three level boost type AC-DC converter under load variations for PI-fuzzy controller combination. If the load power is varied from 100 W to 25 W, the output voltage is maintained at 48V. THD lies in the range from 2% to 3% which satisfy IEEE-516 specifications. Power factor of the circuit is almost unity. The efficiency of the converter is around 90%.

Figure 5c shows the supply side voltage/current signals for PI-Fuzzy (voltage-current) controller combination. Zero phase shift is maintained by both voltage & current signals providing unity power factor. Source current waveform is almost sinusoidal with very less distortions of 3.23% THD.

Figure 5d shows the FFT analysis of source current with PI-fuzzy combination. Constant output voltage is obtained during wide
obtained even for unsymmetrical capacitances. Source current THD obtained are same as for obtained with the capacitance matched condition. Figure 5g and 5h pictures out that regulated output voltage and balanced capacitor voltages are obtained during instant toggling of load power from 25 W to rated load (100 W). The THD value obtained is reduced value of 2.86% while using FLC which is much better result compared to 9.16% obtained when using PI as current controller. Stability analysis of boost type three level converter is done by varying source side voltage (28 V to 36 V) and the waveforms are checked out as shown in figure 5i and 5j. Here also output voltage is well regulated with balanced capacitor voltages. The THD value obtained is reduced value of 2.74% while using FLC which is better result compared to 3.65% obtained when using PI as current controller.

Figure 5e: Simulated results for three level converter at 100 W under capacitance mis-matched condition $C_1 = 7360\mu F$ and $C_2 = 6530 \mu F$ with PI voltage controller and PI current controller. Figure 5f: Simulated results for three level converter at 100 W under capacitance mis-matched condition $C_1 = 7360\mu F$ and $C_2 = 6530 \mu F$ with PI voltage controller and fuzzy current controller.
Figure 5g: Simulated results for three level converter during load change from 25 W to 100 W at t = 4s with PI voltage controller and PI current controller. Figure 5h: Simulated results for three level converter during load change from 25 W to 100 W at t = 1.6s with PI voltage controller and fuzzy current controller.
Figure 5i: Simulated results for three level converter during supply variations from 28 V to 36 V at t = 0.8s with PI voltage controller and PI current controller. Figure 5j: Simulated results for three level converter during supply variations from 28 V to 36 V at t = 0.9s with PI voltage controller and fuzzy current controller.
control for marine applications. Analysis for sudden disturbances in load as well as source side for three level converter are checked and verified that fuzzy logic current controller produces better power quality enhancement. THD of source current have been limited within IEEE 519 standard limit for wide variations of load with power factor near to unity.

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**References**


**Conclusion**

The paper deals with the design and modeling of fuzzy current controller in multiloop interleaved control for single phase three level boost type AC-DC converter in MATLAB/Simulink. Main benefit of three level converter is the ability to generate high voltage with reduced voltage stress on the switches. Fuzzy logic controller as current controller instead of conventional PI controller integrated in multiloop interleaved control method reduces the THD value to 3.23% without adding any filter on supply side and power factor to be unity and also fuzzy current controller eliminates the necessity of feed forward loop in multiloop interleaved...


