Micro-hydro generator fed frequency adaptive sliding mode controlled air conditioning system for remote and hilly areas

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Abstract
This paper presents a micro-hydro generator driven frequency adaptive sliding mode (FASM) control-based improved power quality permanent magnet brushless DC motor (PMBLDCM) driven air conditioning system for remote and hilly areas. In such locations, the grid availability is poor or limited. The self-excited asynchronous generator (SEAG) is highly suitable for micro-hydro power generation. The voltage and frequency regulations of SEAG systems are very poor. Therefore, an improved power quality FASM control of a new zeta function based modified CSC (ZFM-CSC) converter scheme is developed to drive the micro-hydro power driven SEAG fed air conditioning system. The conventional air-conditioning schemes are suitable for the grid fed system, where the frequency and voltage remain constant. However, these conventional control schemes are not suitable for a standalone SEAG based micro-hydro generator driven air conditioners since the frequency and voltage of this system vary frequently at different loadings and dynamic operating conditions. This leads to an incorrect estimation of reference source current in a conventional system, which in turn affects the system stability. The sudden change of loads in a conventional air conditioning system may de-magnetize and de-stabilize the micro-hydro driven SEAG. The experimental and simulated results presented validate the robustness of this system.

1 INTRODUCTION

In the hilly and remote locations, the electrical grid power availability is limited or not available due to the transmission and distribution losses consideration. The hilly and remote areas are usually rich in natural resources that can be utilized as a source of micro hydro power generation. The electromechanical systems such as SEAG are found highly suitable for such standalone applications. In this generating system, the frequency and voltage levels are so inconsistent due to variations in loads and in input mechanical power delivered by the turbine. A typical SEAG’s output voltage varies from 130 to 230 V from full load to no load condition. A micro hydro driven SEAG based air-conditioning system may be used in hilly and remote locations to meet the air-conditioning requirement of these areas. Adding to it, the air conditioning system has large fluctuations in dynamic loading conditions. Therefore, a suitable control is required to develop a drive for the air conditioning system, which is fed by such a standalone power generator. Apart from it, these PMBLDCM fed air conditioning systems are largely implemented at household, industrial and corporate cooling applications, due to the high efficiency, silent operation, compact size, high reliability, and low maintenance requirements. However, in a conventional system, a PMBLDCM fed air conditioning system demands non-sinusoidal current and conventional PI based controllers are not suitable to deal with fluctuating load conditions. The optimal control scheme and capacity allocation analysis of such a PMBLDCM based air conditioning system considering the area control error, have been presented in [1]. An implementation of an optimization control scheme of a load control scheduler for large air conditioning loads using relaxed dynamic programming, has been reported in [2]. A PFC
Cuk converter based PMBLDCM drive using the voltage control method for air conditioner, has been investigated and implemented in [3]. A frequency regulation scheme for air conditioner has been reported in [4]. The scheme presented in this work, integrates highly decentralized air conditioning system. A detailed survey of energy management techniques for air conditioners using computational intelligence, has been presented in [5]. An intelligent air conditioning system using broadcasting control in power line carrier technology has been reported in [6]. A model predictive control of air conditioning system of distributed nature has been presented in [7]. The control scheme presented herein rapidly compensates the fluctuations in the solar power. The modeling of inverter based air conditioner has been presented in [8]. It provides the services for frequency regulation in the system. The direct load control of air conditioner using fast dispatch model has been presented in [9].

The effect on voltage recovery of transient faults in air conditioning system, has been investigated in [10]. Hajipour et al. [11], have reported an improved aggregated model of residential air conditioners for FIDVR studies. Fu [12] has presented the temperature based power probabilistic flow control method considering stochastic variables of high dimension. A fair method of allocating the power to air conditioning system in smart grid has been presented in [13]. The modelling and simulation study of common mode noise produced by inverter based air conditioning system has been discussed in [14]. A control scheme based on DC link voltage regulation of an electrolytic capacitor less PMSM drive has been reported in [15]. A scheme for energy saving in air conditioning system of data centres has been investigated in [16]. A MPPT controller using single sensor scheme for wind driven induction generators has been reported in [17]. An integrated small hydro and wind energy generation system with reduced number of converters have been reported in [18].

A control scheme of solar and small hydro micro grid has been presented in [19]. The output optimization of the inverter air conditioning system using energy storage modelling has been presented in [20]. A consensus control scheme of an inverter air conditioner has been discussed in [21]. A solar air cooler system using standalone PMBLDCM with improved efficiency has been presented in [22]. As per the survey of literature presented in [1–22], the small hydro driven air conditioning systems for remote locations, have not been explored yet. The BLDC motor drives are widely used in various applications such that electrical vehicles, air conditioners, fans, solar water pumping systems and automation systems [23]. These motors are powered through a diode bridge rectifier fed from a single-phase AC mains followed by a DC link capacitor and a voltage source inverter (VSI). The conventional VSI based PMBLDCM drive suffers from the power quality problems such as poor power factor (PF), high total harmonics distortion (THD) and crest factor (CF) of source current, due to uncontrolled charging of the DC link capacitor, which results in a pulsed current waveform having a peak value higher than the amplitude of the fundamental component of source current. Various power factor correction (PFC) schemes for a PMBLDCM drive [24] have been reported in the literature. The analysis of DC-DC converters has been reported in [25]. The design and analysis of slot-less PMBLDCM is reported in [26]. A five-phase permanent magnet motor drive is introduced in [27]. A hybrid micro BLDC motor is reported in [28]. Various rotor configurations for BLDC motor are reported in [29]. The reduced torque ripple operation of PMBLDCM air conditioning system using direct torque control technique have been reported in [30]. A back-EMF detection procedure for sensorless PMBLDCM drive has been reported in [31]. The determination of magnetizing quality of BLDC motors, has been reported in [32]. An optimization method for designing a BLDC motor for solar airplane is presented in [33]. A real time hybrid bang-bang fuzzy controller is presented in [34]. A solar driven BLDC motor based pumping system is reported in [35].

A large number of power factor correction schemes have been reported in the available literature, which are very useful for the grid connected systems. However, the standalone generator driven air-conditioning system requires significant modifications in conventional control system for proper functioning of the system. The frequency of a grid connected system remains constant, whereas the frequency of a standalone SEAG system varies with different loading and operating conditions. In conventional system, a fixed peak value of source voltage is considered for estimating the unit template, which is used for generation of a reference current signal. However, in proposed micro-hydro driven air conditioning system, the voltage and frequency of single phase asynchronous generator, have the poor regulation therefore, the peak value of voltage also fluctuates, which leads to an incorrect estimation of reference source current and in turn it affects the system stability. The Table 1 shows the comparison of the proposed scheme with the reported conventional schemes.

This paper proposes a frequency adaptive peak estimation scheme based unit template and reference source current of the generation system. It is highly suitable and it also significantly improves the system stability of this single phase SEAG fed air conditioning system. The sliding mode feedback control further improves the system stability. This paper examines a power factor correction (PFC) frequency adaptive sliding mode feedback controlled modified CSC-PMBLDCM air conditioning system that is fed by a standalone generator. The proposed power factor control with modified CSC converter based topology

| Parameters                                | Buck-boost | SEPIC | Luo | Proposed scheme |
|-------------------------------------------|------------|-------|-----|-----------------|
| Input current ripple                      | High       | High  | High| Low             |
| No. of components in converter            | 4          | 6     | 6   | 4               |
| Overshoot in DC link voltage              | Yes        | Yes   | Yes | No              |
| Settling time during dynamic condition    | High       | High  | High| Low             |
| Stability                                 | Poor       | Poor  | Poor| Stable          |
| Requirement of LC filter                  | Yes        | Yes   | Yes | No              |

| TABLE 1 Performance of different DC/DC converters with air conditioning system |
significantly improves the power quality and performance of the system in steady state as well as dynamic conditions.

The followings research gaps of the conventional schemes [1–22] have been removed in the proposed scheme:

• There is no scheme reported in the literature which address the technical issues, challenges and their mitigation techniques for standalone small hydro power generator fed air conditioning systems.

• The proposed scheme also has a unique feature of frequency adaptive unit template generation, which makes the scheme highly suitable for power factor correction in standalone renewable energy generation-based power source driven PMBLDCM fed air conditioning system.

• It is well known that the system frequency of SEAG system does not remain constant but it varies under various operating conditions such as load perturbations or variation in input mechanical power delivered to the prime mover of the generator.

• The proposed scheme is highly suitable for the PMBLDCM fed air conditioning system, which is fed by the above said power generation source with poor frequency regulation.

• The proposed scheme is based on an adaptive sliding mode feedback control, which removes all overshoots and undershoots in the DC link voltage.

• The possibilities of the fluctuation/oscillations/overshoot in speed of PMBLDCM fed air conditioning system are also removed during the starting period and under load perturbation conditions.

The paper has following 7 sections. The introduction and research gap are presented in the Section 1. The Section 2 deals with the systems description of the proposed scheme. In Section 3 control algorithm and mathematical analysis of the system has been presented. The simulated performance of the system has been discussed and analyzed in Section 4. The details of the experimental setup and its performance has been described in Section 5. Comparison of the proposed scheme with the other conventional schemes has been described in Section 6. The conclusions of the paper have been presented in Section 7.

2 SYSTEM DESCRIPTION

The proposed PFC zeta function based modified canonical switching cell (ZFM-CSC) converter using sliding mode feedback control for a PMBLDCM drive fed air conditioning system includes a single phase source, an input AC filter, a rectifier used is a diode bridge rectifier, a ZFM-CSC converter controlled using a novel PFC based speed control scheme for PMBLDCM drive, a three phase VSI and a PMBLDCM motor. The rectifier converts the AC power into DC power. The proposed control scheme operates the ZFM-CSC converter in such a manner that the source current remains sinusoidal and in-phase with the source voltage under all operating conditions. The Hall effect sensors provide the rotor position feedback to the controller in order to generate three-phase output voltages of suitable shape for the PMBLDC motor. The proposed ZFM-CSC converter controls the DC Link voltage of the three-phase VSI, which controls the speed of PMBLDC motor and in turn drives the compressor of air conditioning system. The detailed control algorithm along with circuit schemes for the proposed PFC ZFM-CSC PMBLDCM fed air conditioning system, is presented in Figure 1 for continuous current mode of operation. The scheme presented in Figure 1, is applicable for the PFC operation of PMBLDCM fed air conditioning system under varying system frequency. This scheme is found highly suitable for high, medium and low power PMBLDCM fed air conditioning system for remote and hilly areas. An experimental setup of proposed system is shown in Figure 2.

In a conventional system, a fixed peak value of source voltage is considered for estimating the unit template, which is used for generation of a reference current signal. However, in the proposed micro-hydro driven air conditioning system, the voltage and frequency of single phase asynchronous generator, have the poor regulation, therefore, the peak value of voltage also fluctuates. It leads to an incorrect estimation of reference source current, which in turn affects the system stability. Therefore, this paper proposes a frequency adaptive peak estimation (FAPE) scheme based unit template and reference source current for the generation system. It significantly improves the system stability in a single phase SEAG fed air conditioning system. The flowchart of FAPE block of the proposed scheme is shown in Figure 3. The FAPE technique shown in Figure 3, is used in the proposed system to generate a quadrature signal of SEAG voltage. The input voltage $v_p(t)$ is passed through a low-pass filter before feeding it to the FAPE block, to remove measured noise from the signal. The filtered voltage is sampled at every 30 μs and stored in an array. The value of each sample is compared with the previously taken sample. If the previous sample value is less than zero and new sample value is greater than zero, the FAPE block registers this point as a positive zero crossing point of an input voltage. The value of estimated time period of the input voltage is used to introduce 90° phase shift (delay time equal to period/4) in the next cycle of the system voltage to generate the quadrature signal of SEAG voltage. As the SEAG frequency and voltage depend on the loading condition and seasonal changes, it is not possible to generate 90° phase shifted signal by adding fixed time delay into each cycle of system voltage signal. Therefore, an estimated time delay is introduced in each cycle of the SEAG voltage to obtain quadrature signal (equal to one fourth of the estimated time period of its previous cycle), and this 90° phase shifted signal is required to generate unit template of input voltage as required by PFC input.

The sliding mode feedback control further improves the system stability. The reference speed of the motor after a multiplication with a speed loop gain factor, is compared with the DC link voltage of the voltage source inverter (VSI) in order to estimate the error in DC link voltage. An error in the DC link voltage is processed through a speed PI controller in order to ensure the zero error in the speed of the drive. The output of this speed PI controller is multiplied with the frequency
adaptive unit template of the system voltage to generate a reference DC current signal of the drive. This reference current signal is compared with the rectified DC source current, and this current error is processed through a sliding mode feedback controller. The output of sliding mode feedback controller is fed to the PWM generation block. This block generates the PWM gating signal to control the switching operation of switch Sw1 in order to achieve the desired performance of the PMBLDCM fed air conditioning system. In the proposed scheme, the speed of the PMBLDCM drive is controlled by adjusting the DC link voltage of the VSI. This DC link voltage of VSI is controlled through switch Sw1.

The operation of this switch is controlled through the proposed sliding mode feedback controller in order to reduce the possibility of an over voltage across the switch. The ZFM-CSC converter reduces the voltage ripple in the DC link voltage with reduced switching losses due to use of single switch and high stored energy in circuit components.

3 | CONTROL ALGORITHM, AND ANALYSIS OF THE SYSTEM

This section consists of control algorithm, design and analysis of the system.

3.1 | Control algorithm

The proposed system contains two loops one is temperature control loop and the PFC and duty cycle generation loop.

3.1.1 | Temperature control loop

The value of actual room temperature ($T$) is compared with a reference value of room temperature $T^*$ in order to calculate the error in the temperature.

$$T_e = T^* - T.$$  (1)
Here $T^*$ is the reference value of the temperature set by the consumer. $T$ is the actual value of the room temperature. $\Delta T$ is the difference between reference value and actual value of room temperature. According to the difference in temperature, the reference voltage for the compressor’s PMBLDCM motor is decided using Table 2.

The DC link voltage ($V_{DL}$) at input side of VSI is compared with a reference DC link voltage $V^*_{DL}$ in order to calculate the error in the DC link voltage.

$$V_{DL} = V^*_{DL} - V_{DL}.$$ (2)  

The error in the DC link voltage is processed through proportional-integral (PI) controller.

$$V_{sp}(k) = V_{sp}(k-1) + K_{isp}V_{DL}(k) - V_{DL}(k-1) + K_{isp}V_{DL}(k),$$ (3)

where $K_{isp}$ and $K_{isp}$ are integral and proportional constants of the speed PI controller.

### 3.1.2 PFC and duty cycle estimation loop

The source voltage ($v_s$) is processed through the phase shifting block to obtain a 90° phase shifted signal ($v_{qg}$) of the source voltage in order to obtain a frequency adaptive phase shifted signal of the source voltage. The rectified output voltage ($V_R$) is determined by $V_{peak}$ to obtain a unit template of source voltage ($u_p$)

$$u_p(k) = \frac{V_{peak}(k)}{V_{peak}(k)}.$$ (4)

The output of voltage PI controller Equation (3) is multiplied with unit template of SEAG output voltage Equation (4) in order to obtain reference value of rectified current.

$$I_{sp}(k) = V_{sp}(k) \times u_p(k).$$ (5)

The reference source current ($i_{sp}$) is compared with the sensed source current ($i_s$) to obtain an error in source current.

$$\dot{I}_{sp}(k) = I_{sp}(k) - I_s(k) = \dot{I}_{sp1}(k).$$ (6)

This current error is processed through the sliding mode feedback controller.

$$\dot{I}_{g2}(k) = \frac{1}{I_g} \left\{ I_{g1}(k) - I_{g2}(k) \right\}.$$ (7)

The $\dot{I}_{g2}(k)$ passed through a unit delay block (1/Z) to obtain $I_{g2}(k)$ delayed by one sampling instant.

A function block, which outputs either +1 or -1 according to the value of input (M, N), is processed as,

$$\dot{M} = \alpha \dot{I}_{g1}(k) \dot{I}_{g2}(k), \quad \dot{N} = \beta \dot{I}_{g1}(k) \dot{I}_{g2}(k).$$ (8)

### TABLE 2  Temperature vs. voltage

| $T^*$ (°C) | >20 | 15–20 | 15–10 | 10–3 | <3 |
|------------|-----|-------|-------|------|----|
| $V^*_{DL}$ (V) | 310 | 230 | 160 | 110 | 70 |
The duty cycle of the converter is calculated as follows

$$D = \pm Z_1 I_{g1} \mp Z_2 I_{g2}. \quad (9)$$

The output of the sliding mode feedback controller is processed through the PWM generator. The output of the PWM generator is fed to the power electronic switch (IGBTs) through the optical isolation and driver circuit. The desired control of the DC link voltage and improved power quality operation of proposed PMBLDCM drive are achieved through controlling the switching operation of the switch ($s_w$).

### 3.2 Design of PFC sliding mode controlled ZFM-CSC converter

This section presents the design of proposed PFC ZFM-CSC converter to operate in CCM (continuous conduction mode) such that the transfer inductor current $i_{L1}$ and voltage across transfer capacitor $C_1$ remain continuous in every switching period. The design procedure is presented for power rating of 700 W. All the component of the system may be redesigned for any higher rating in the similar manner. The variation in DC Link voltage is considered from 70 to 310 V (maximum value of output voltage) for sufficient range of variation in speeds.

The transfer capacitor of output voltage for sufficient range of variation in speeds.

The input source voltage, $v_s$ is represented as follows.

$$v_s(t) = V_m \sin (2\pi f_{L1} t) = 220 \sqrt{2} \sin (314 t) V,$$ \quad \text{(10)}

where $V_m$ is the peak input voltage (i.e. $\sqrt{2}V_m$), $f_{L1}$ is the system frequency (i.e. 50 Hz).

The instantaneous voltage across the combination of switch and inductor is represented as follows.

$$v_{g, in}(t) = |v_s(\omega t)| = \left| 220 \sqrt{2} \sin (314 t) \right| V. \quad \text{(11)}$$

The output voltage, $V_{DL}$ of the converter is as follows.

$$V_{DL} = 1 - 2D \frac{V_g}{1 - D} \quad \text{(12)}$$

where $D$ represents the duty cycle.

An instantaneous duty cycle $D(t)$ is calculated as follows.

$$D(t) = \frac{V_{DL} - V_{g}(t)}{V_{DL} + 2V_{g}(t)} = \frac{V_{DL} - |V_m \sin (\omega t)|}{V_{DL} + 2 |V_m \sin (\omega t)|} \quad \text{(13)}$$

Since the speed of the motor depends on the DC link voltage $V_{DL}$ of VSI, therefore, the instantaneous power, $P_{g, in}$ may be considered as linear function of the DC link voltage $V_{DL}$ as,

$$P_{g, in} = \left( \frac{P_{peak}}{V_{DL, peak}} \right) V_{DL}, \quad \text{(14)}$$

where $V_{DL, peak}$ is the maximum value of the DC link voltage and $P_{peak}$ is rated power of the converter.

#### 3.2.1 Design of transfer inductor $L_1$

The value of transfer inductor $L_1$ is calculated in continuous conduction mode of operation for permissible limit ($\lambda$) of the inductor current $I_{L1}$. The critical value of inductor $L_1$ is calculated as follows.

$$L_1 = \frac{V_{g, in}(t)D(t)}{\lambda I_{g, in}(t)f_S} = \frac{R_d D(t)}{\lambda f_S} = \left( \frac{V_m^2}{P_{g, in}} \right) D(t) \frac{f_S}{\lambda f_S}, \quad \text{(15)}$$

where $R_d$ is an equivalent input resistance, $f_S$ is switching frequency of the converter switch and $P_{g, in}$ is an instantaneous input power. The value of switching frequency decides the losses in the switch and the size of transfer inductor $L_1$. The switching frequency of 10 kHz is considered in this design procedure. The maximum current through inductor appears when the DC link voltage is maximum that is 310 V at maximum power ($P_{g, peak}$) and the at the minimum source voltage ($V_{g, min}$) that is 85 V. Hence, the minimum value of the transfer inductor for CCM mode is calculated as follows [37].

$$I_{L1, min} = \left( \frac{V_m^2}{P_{g, peak}} \right) \frac{D(t)}{\lambda f_S} = \left( \frac{85^2}{700} \right) \frac{0.7206}{0.3} \times 10000 \approx 2.47 \text{ mH},$$ \quad \text{(16)}

where the permissible limit in the inductor current ripple is taken 30%. The value is selected more than 2.47 mH for operating the converter in CCM, so the value of transfer inductor is taken 4 mH for this system.

#### 3.2.2 Design of transfer capacitor $C_1$

The transfer capacitor $C_1$ is calculated as follows [4].

$$C_1 = \frac{V_{DL, D(t)}}{\Delta V_{C1}(f_S R)} = \left( \frac{V_{DL, D(t)}}{V_{g, in}} \right) \frac{f_S R}{\eta}, \quad \text{(17)}$$

where $\eta$ is the ripple voltage across transfer capacitor $C_1$, voltage across $C_1$ is $V_{C1}$ and load resistance is equal to $R_L$, which is calculated as $R_L = V_{DL}^2/P_{g, in}$. The maximum value of transfer capacitor $C_1$ is calculated as follows.

$$C_{1, max} = \frac{V_{DL, max} D(t)}{\eta \left( \sqrt{2} V_{g, max} + V_{DL, max} \right) f_S R_L} = \frac{310 \times 0.4481}{0.1 \left( 270 \sqrt{2} + 310 \right) 10000 \times 192.2} = 1.022 \mu F$$ \quad \text{(18)}
3.2.3 Design of output inductor \( L_o \)

The value of output inductor \( L_o \) is calculated for CCM mode of operation for permissible ripple limit (\( \gamma \)) in the inductor current \( I_{L_o} \). The value of inductor \( L_o \) is calculated as follows [36].

\[
L_o = \frac{V_{DL} \times (1 - D)}{\gamma \times I_{L_o} \times f_s} = \frac{V_{DL} \times D}{\gamma \times I_g \times f_s} = \frac{R_g \times V_{DL} \times D}{\gamma \times V_g \times f_s}
\]

\[
= \left( \frac{V_g}{P_{g,peak}} \right) \frac{V_{DL}}{\gamma \times \sqrt{2} \times f_s} \left( \frac{V_{DL} \times \sqrt{2} \times V_g}{V_{DL} + 2 \sqrt{2} \times V_g} \right)
\]

(19)

The maximum current through the inductor appears when the DC link voltage is maximum that is at maximum power \( (P_{max}) \) and at the minimum source voltage \( (V_g,min) \). Hence the inductor \( L_o \) for maximum permissible ripple (\( \gamma \)) in current of 30% is calculated as follows [36].

\[
L_{o,\text{min}} = \left( \frac{V_g}{P_{g,peak}} \right) \frac{V_{DL,\text{max}}}{{\gamma \times \sqrt{2} \times f_s} \left( \frac{V_{DL,\text{max}} \times \sqrt{2} \times V_g}{V_{DL,\text{max}} + 2 \sqrt{2} \times V_g} \right)}
\]

\[
= \left( \frac{85^2}{700} \right) \frac{310}{0.3 \times \sqrt{2} \times 85 \times 10,000} \left( \frac{310 - 2 \times 85}{310 + 2 \times 85} \right)
\]

\[
= 3.06 \text{mH}
\]

Hence, the value of \( L_o \) is chosen 3 mH for operating the converter in CCM of operation.

3.2.4 Design of DC link capacitor \( C_o \)

The DC link capacitor \( C_o \) is determined as follows [4].

\[
C_o = \frac{I_o}{2 \omega \Delta V_{DL}} = \left( \frac{P_{g,peak}}{V_{DL}} \right) \frac{1}{2 \omega \times V_{DL}},
\]

(21)

where \( \delta \) represents the allowable ripple in DC link voltage. Considering the minimum value of DC link voltage (70 V),

\[
C_o = \left( \frac{P_{\text{min}}}{V_{DL,\text{min}}} \right) \frac{1}{2 \omega \times V_{DL,\text{min}}}
\]

\[
= \left( \frac{113}{70} \right) \frac{1}{2 \times 314 \times 0.20 \times 70} \approx 1836 \mu F.
\]

Therefore, the DC link capacitor of 2200 \( \mu F \) is selected for this application.

3.2.5 Design of shunt capacitor filter \( C_{Sh} \)

A shunt capacitor filter \( (C_{Sh}) \) is connected across the source as calculated as follows [36].

\[
C_{Sh} = \frac{L_o}{\omega L \times V_g(t)} \tan(\theta) = \left( \frac{P_{g,\text{max}} \sqrt{2} / V_{g,\text{max}}}{\omega L \sqrt{2} v_g} \right) \tan(\theta)
\]

(23)

The maximum shunt capacitor is designed for the maximum value of input power at maximum value of source voltage.

\[
C_{Sh,\text{max}} = \frac{\omega \sqrt{2 V_{g,\text{max}}}}{700 \sqrt{2 / 220}} \tan(\theta) \approx 803.97 \text{nF}
\]

Hence, the value of shunt capacitor filter \( C_{Sh} \) is selected less than the maximum value, so that the value of \( C_{Sh} \) is considered 470 nF for this design.

3.3 Working of PFC sliding mode controlled ZFM- CSC converter

The converter is operating in continuous conduction mode (CCM) of operation, From Figure 4, it is clear that the converter is operating in two different modes.

The working mode depends on the position of the switch, in mode-I the converter’s switch \( S_{sw1} \) is turned ON and in mode-II, the converter’s switch \( S_{sw1} \) is turned OFF.

MODE-I: The converter’s input inductor \( L_I \) is charged with rectified source voltage \( V_R \) when the switch \( S_{sw1} \) is turned ON as shown in Figure 4(a). The transfer capacitor \( C_I \) discharges to the load through an output inductor \( L_o \). The transfer capacitor \( C_I \) is initially charged and it delivers its energy to input inductor \( L_I \) via short circuit path. The output capacitor \( C_o \) is discharged via a transfer capacitor \( C_I \) and an output inductor \( L_o \) in this mode.

MODE-II: The converter’s diode \( D_I \) starts conducting when switch \( S_{sw1} \) is turned OFF as shown in Figure 4(b). The input inductor \( L_I \) discharges and delivers its energy to transfer capacitor \( C_I \).

The transfer capacitor delivers its energy to the load and it charges the output capacitor \( C_I \). The input inductor \( L_I \) discharges linearly and the transfer capacitor \( C_I \) is charged through an input rectified voltage and an input inductor \( L_I \).
3.4 | Small signal analysis of PFC sliding mode controlled ZFM- CSC converter

This section consists of small signal model (SSM) for proposed converter. The state space averaging is used to obtain the small signal model for the converter.

State variables chosen for modelling are as follows.

- $i_{L1}$ Transfer inductor current
- $i_{LO}$ Output inductor current
- $V_{C1}$ Transfer capacitor voltage
- $V_{DL}$ Output Voltage

Following assumptions are made:

- All components are ideal and loss free.
- The converter is operating in continuous mode of conduction.

By Figure 4(a), it can be observed that the converter operates in two different modes.

3.4.1 | Mode I: When converter switch is 'ON'

The converter inductor is charged with source voltage $V_g$ as,

$$\frac{d}{dt}(L_1 i_{L1}) = V_g - V_R D$$

(25)

The transfer capacitor $C_1$ is initially charged and as the switch turns on, the transfer capacitor $C_1$ transfers its energy to transfer inductor via short circuit path.

The current and voltage laws given by Kirchhoff, are applied on the loop to obtain the followings,

$$\frac{d}{dt}(VC_1) = i_{LO} D$$

(26)

$$\frac{d}{dt}(VL_0) = (VDL + VC_1) D$$

(27)

The output capacitor is discharged by supplying load.

$$\frac{d}{dt}(VC_0) = -\left(i_{LO} + \frac{VDL}{R}\right) D$$

(28)

3.4.2 | Mode II: When converter switch is 'OFF'

The converter toggles into this mode, when the switch is turned off and the diode starts conducting. The transfer inductor discharges its energy to the load and it charges the output.
An input inductor discharges linearly and the transfer capacitor is charged through input voltage and input inductor.

\[
\left( L_O \frac{di_{LO}}{dt} \right) (1 - D) = (V_{DL} - V_R) (1 - D)
\]  

Adding equations for Mode I (Equations (25)–(28)) and Mode II (Equations (29)–(32)) to obtain average equations.

\[
\left( C_1 \frac{dV_{C1}}{dt} \right) (1 - D) = -i_{L1} (1 - D)
\]

\[
\left( C_O \frac{dV_{C1}}{dt} \right) (1 - D) = - \left( i_{LO} + \frac{V_{DL}}{R} \right) (1 - D)
\]

The perturbation has been introduced for chosen state variables and quantities of above equations,

\[
i_{L1} = i_{L1} + \hat{i}_{L1}, i_{LO} = i_{LO} + \hat{i}_{LO}, V_{C1} = V^\wedge_{C1} + \hat{V}, V_R = V_R + \hat{V}
\]

\[
V_{DL} = V_{CO}, \text{as output capacitor and load are connected in parallel and the voltage is equal.}
\]

\[
\left( C_O \frac{dV_{DL}}{dt} \right) = - \left( i_{LO} + \frac{V_{DL}}{R} \right)
\]

Using these perturbed equations in Equations (31)–(34) and by neglecting the second order terms, following equations are obtained

\[
L_1 \frac{\hat{d}i_{L1}}{dt} = (D + \hat{d})(V_R + \hat{V}) + (1 - D - \hat{d})(-V^\wedge_{C1} - \hat{V})
\]

\[
L_1 \frac{\hat{d}i_{L1}}{dt} = \hat{d}V_R + D \hat{V} + (1 - D)(- \hat{V}^\wedge_{C1}) + \hat{d}V^\wedge_{C1}
\]

\[
L_O \frac{di_{LO}}{dt} = (D + \hat{d})(V^\wedge_{C1} + \hat{V} + V_{DL} + \hat{V}_{DL}) + (1 - D - \hat{d})(V_{DL} + \hat{V}_{DL} - V_R - \hat{V}_R) = D \hat{V}^\wedge_{C1} + D \hat{V}_{DL} + \hat{d}V^\wedge_{C1} + \hat{d}V_{DL} + (1 - D)(V_{DL} - V_R) - \hat{d}(V_{DL} - V_R)
\]

\[
\left( C_1 \frac{\hat{d}V^\wedge_{C1}}{dt} \right) = (D + \hat{d})(i_{LO} + \hat{i}) + (1 - D - \hat{d})(-i_{L1} - \hat{i}_{L1}) = \hat{d}i_{LO} + D \hat{i}_{LO} + (1 - D)(- \hat{i}_{L1}) + \hat{d}i_{L1}
\]

\[
\left( C_O \frac{\hat{d}V_{DL}}{dt} \right) = - \hat{i}_{LO} - \hat{V}_{DL} - \hat{V}
\]

Now, by taking Laplace transformation of these above equations.

\[
sL_1 i_{L1}(s) + (1 - D) V^\wedge_{C1}(s) = \hat{d}(s)R + \hat{d}(s)C_1 + D \hat{V}_R(s)
\]

\[
sL_O i_{LO}(s) - D V^\wedge_{C1}(s) - \hat{V}_{DL}(s) = \hat{d}(s)V^\wedge_{C1} + \hat{d}(s) + (1 - D) \hat{V}_R(s)
\]

\[
sC_1 V^\wedge_{DL}(s) + \hat{i}_{LO}(s) + \frac{\hat{V}_{DL}}{R} = 0
\]

From above derived equations, the small signal model of the converter can be derived as shown in Figure 4(b).

The matrix form of the above derived equations.

\[
\begin{bmatrix}
  sL_1 & 0 & 0 & 0 & \hat{i}_{L1}^\wedge(s) \\
  0 & sL_O & -D & 0 & \hat{i}_{LO}^\wedge(s) \\
  -D & 0 & sC_1 & 0 & \hat{V}_{C1}^\wedge(s) \\
  0 & 0 & 0 & sC_O & \frac{V_{DL}}{R}^\wedge(s)
\end{bmatrix}
= \begin{bmatrix}
  D & 0 & 0 & 0 & \hat{V}_R^\wedge(s) \\
  V_R + V_{CO} & (i_{LO} + \hat{i}_{L1}) & \hat{d} & (1 - D) & 0 & \hat{V}^\wedge_{C1}(s) \\
\end{bmatrix}
\]

So, from the above equations, the desired transfer functions for the converter can be obtained.
The transfer function of the ZFM-CSC converter used in this scheme, is given as follows.

\[
T_o = \frac{-8.467 \times 10^{10}s^2 + 2.995 \times 10^{10}s - 5.774 \times 10^{13}}{s^4 + 3.529s^3 - 4.971 \times 10^{10}s^2 - 1.75410^9s - 5.92310^{10}}
\]  

(46)

The Bode plot response of the system is shown in Figure 4(c). The Bode plot shows that the system has phase margin of 91.6° and infinite gain margin that significantly shows that the system is in stable condition of operation.

4 | SIMULATED PERFORMANCE

The proposed micro-hydro generator driven frequency adaptive sliding mode (FASM) control-based power quality improved permanent magnet brushless DC motor (PMBLDCM) air conditioning system for remote and hilly areas, is simulated using MATLAB/Simulink environment. This section presents simulated performance of proposed system in Figure 5(a–d). The improved power quality performance along with steady state and dynamic performance, is evaluated to confirm satisfactory operation of the proposed system.

4.1 | Steady state performance

The steady state performance of the ZFM-CSC converter and PMBLDC motor used in the system, is shown Figures 5(a) and 5(b), respectively, at rated condition.

The results presented in Figure 5(a), show the source voltage and current both are in phase and sinusoidal. The DC link voltage is maintained constant at 160 V during a steady state operation. An inductor current and capacitor voltage are also
The waveform of an inductor current is continuous in nature that confirms the continuous conduction mode of operation of the converter.

Figure 5(a) shows a satisfactory performance of a ZFM-CSC converter. The steady state performance of a PMBLDCM drive used in proposed scheme is shown in Figure 5(b) using source current ($i_{g}$), DC link voltage ($V_{DL}$), motor's electromagnetic torque ($T_{M1}$), motor stator current ($i_{M1}$) and back EMF ($e_{M1}$) of the motor. The waveforms shown in Figure 5(b) confirm that the motor is working in stable condition at steady state operation of proposed scheme.

The power quality performance using harmonic spectra of source current are shown in Figure 5(c) at reduced source voltage (i.e. 90 V) and in Figure 5(d) at rated source voltage (i.e 220 V) at constant DC link voltage. Figures 5(c) and 5(d) show that power quality indices are maintained within the acceptable IEC 61000-3-2 and IEEE 519 limits.

5 | HARDWARE IMPLEMENTATION

A hardware setup is developed as shown in Figure 1(b) in the laboratory to validate the response of the proposed PFC ZFM-CSC converter powered PMBLDCM drive system for air conditioning. The hardware setup consists of a 1 HP PMBLDC motor, a PFC ZFM-CSC converter and VSI for PMBLDC motor, DSP (d-SPACE1104) is used to implement the controller having sampling time of 30 micro second. A digital storage oscilloscope is used to obtain performance of proposed drive system. The power quality indices of source side are recorded by a harmonic spectrum in a power analyzer (Fluke 43b).

This section demonstrates the performance of proposed system obtained during steady-state operating condition shown in Figures 6–8 at rated source voltage, and dynamic performance during change in source voltage, change in the load and a change in reference speed. The improved power quality indices are achieved as shown in Figure 8, at the AC mains for different conditions of source voltages at 90 and 220 V are within the acceptable limits of the IEC 61000-3-2 and IEEE 519 standards.

5.1 | Steady state performance

The steady-state performance of PFC ZFM-CSC converter used in proposed system, operating at rated source voltage (220 V) is shown in Figure 6(a).
A unity power factor operation is achieved at the input AC mains since the obtained source current ($i_g$) is sinusoidal in nature and in phase with the source voltage ($v_g$). Figure 6(a) also shows the waveform of converter's switch current ($I_{SW1}$) and converter's switch voltage ($V_{SW1}$).

### 5.2 Steady state performance of PMBLDCM drive

The steady-state performance of proposed PMBLDC motor drive operating at rated source voltage (220 V) with the DC-link voltage (110 V) is shown in Figure 6(d). These waveforms show that a unity PF operation is obtained during steady state operation as the source current ($i_g$) is sinusoidal in nature and in phase with the source voltage ($v_g$). The DC-link voltage ($V_{DL}$) is maintained at the desired value of 110 V and the motor stator current waveform shows that the motor is stable during steady state operation of proposed PMBLDCM drive system for air conditioning application.

### 5.3 Dynamic performance during change in source voltage

Figure 7(a) shows the dynamic performance of proposed PMBLDCM drive air conditioning system during a change in the source voltage from 220 to 90 V. The waveforms of source voltage ($v_g$), source current ($i_g$), DC link voltage ($V_{DL}$), motor stator current ($i_{m1}$) are shown in this figure.

These results presented in Figure 7(a), show that the PMBLDC motor drive system is in stable condition even during sudden change in the source voltage. The DC link voltage remains constant during the change in the source voltage.

### 5.4 Dynamic performance during change in load

Figure 7(b) shows the dynamic performance of proposed PMBLDCM drive system during variation in the load through the waveforms of source voltage ($v_g$), source cur-
Figure 7(c) shows the dynamic performance of proposed PMBLDCM drive air conditioning system during variation in the speed reference using the waveforms of source voltage ($v_g$), source current ($i_g$), DC link voltage ($V_{DL}$), motor stator current ($i_{M1}$). These waveforms show the motor is stable during variation in the DC link due to a change in the reference speed and the source current is sinusoidal during this change.

5.6 Starting performance of PMBLDCM drive air conditioning system

The starting performance of proposed PMBLDCM drive air conditioning system operating at rated source voltage (230 V) is shown in Figure 7(d). Figure 7(d) shows that the PMBLDCM motor is starting very smoothly when the speed reference is varying from 0 to 1200 RPM and from these waveforms, it can be observed that there is no overshoot is present during starting of the motor that confirms the smooth start of PMBLDC motor-drive air conditioning system.

5.7 Power quality indices

The power quality indices confirming the unity power factor operation of proposed system are discussed in this section. Figure 8 shows different power related measured data like source voltage ($v_g$), source current ($i_g$), active ($P_{ac,t}$), reactive ($P_{re,t}$) and apparent ($P_{ap,t}$) powers, power factor (PF), displacement power factor (DPF) and THD of source current.

These above all parameters are measured using a power quality analyzer (Fluke-43B). The THD of the source current is 3.5% and 2.9 % when the converter is operating at 220 and 90 V source voltage, respectively. These results show that a satisfactory PQ performance has been achieved at various source voltages satisfying the limits of the IEC 61000-3-2 and IEEE 519 standards. The experimental and simulated results of proposed scheme prove the robustness of proposed system.

5.8 Discussion on results

The experimental results presented in Figure 6 shows that the maximum voltage stress across converter switch is 500 V and maximum current stress is 14 A. The voltage and current stresses on the switch are quite low and the switching devices with these voltage and current ratings are easily available. The experimental performance of the system during the change in current and the source current to meet the load demand. The DC link voltage has been well regulated under varying load conditions.
source voltage is shown in Figure 7(a). It demonstrates that the DC link voltage has been restored to its reference value within few milliseconds, which is quite less time in comparison to the mechanical time constant of the PMBLDC motor drive of the compressor. Therefore, any fluctuation in the source voltage does not affect the performance of the system. Figure 7(d) shows the soft start performance of the PMBLDC motor drive during the turn on.

The power quality performance of the system is demonstrated in Figure 8. Figure 8(a) shows the waveforms of the source voltage and current. Figure 8(b) demonstrates that the system power factor at 230 V AC. Figure 8(c) shows that the THD of the source current is 4.1% at 230 V AC. Figure 8(d) shows the waveforms of source voltage and current at 90 V AC. Figure 8(e) shows the amount of active and reactive power demanded by the PMBDCM drive based air conditioning system at 90 V AC. Figure 8(f) depicts that the THD of source current is 2.2% at 90 V AC. Figure 8(g) shows the zoomed in spectrum of the harmonic components in source current at 90 V. Figures 8(c), 8(f) and 8(g) demonstrate that the system meets the requirements of IEEE 519 standards of power quality irrespective of the value of the source voltage.

6 | COMPARATIVE ANALYSIS OF PROPOSED SCHEME WITH CONVENTIONAL SCHEMES

This section includes the comparative analysis of proposed scheme with conventional schemes based on simulated performance.

6.1 | Comparison based on variation in DC link voltage with conventional DC-DC converter fed system

This section presents a comparison of performance of proposed scheme of ‘micro-hydro generator driven frequency adaptive sliding mode (FASM) control based power quality improved PMBLDCM air conditioning system for remote and hilly areas’ with other conventional schemes reported in the literature such that (a) buck-boost, (b) SEPIC, (c) Luo converter fed PMBLDCM drive air conditioning system. All these systems are fed with 90 V rms AC input with conventional PI control method used for PFC operation and DC link voltage control.

Figure 9(a) presents the system performance during turn on of a conventional buck-boost converter fed PMBLDCM drive air conditioning system. Figure 9(a) shows that the DC link voltage has over-shoot of 434 V and an under-shoot of 235 V before reaching to the steady state value of 310 V. Figure 9(b) presents the system performance during turn-on of a conventional SEPIC converter fed PMBLDCM drive air conditioning system for remote and hilly areas.

Figure 9(b) depicts that the DC link voltage has undershoot of 200 V followed by an overshoot of 600 V peak and then it slowly settles to steady state value of 310 V. Figure 9(c) presents the system performance during turn-on of a conventional Luo converter fed PMBLDCM drive air conditioning system for remote locations. The waveforms in Figure 9(c) show that the DC link voltage has an overshoot of 390 V peak and then slowly settles down to 310 V peak. Figure 9(d) presents the system performance during turn-on of proposed ZFM-CSC converter based PMBLDCM drive air conditioning system for remote and hilly areas. It can be clearly observed from waveforms in Figure 9(d) that the system’s DC link voltage quickly settles to 310 V without any noticeable undershoot or overshoot.

The system performance shown in Figure 9(a–d), shows that the overshoot in the DC link voltage in conventional buck-boost, SEPIC and Luo converter fed PMBLDCM drive air conditioning system, is quite high in comparison to the proposed
6.2 Comparison based on stability performance with conventional DC-DC converter fed system

This section presents a comparison of stability performance of proposed scheme of micro-hydro generator driven frequency adaptive sliding mode (FASM) control based power quality improved PMBLDCM air conditioning system for remote and hilly areas with other conventional schemes reported in the literature such that (a) buck-boost, (b) SEPIC, (c) Luo converter fed PMBLDCM drive air conditioning system with 90 V input and 310 V desired output.

Figure 10(a) presents the stability performance of conventional buck-boost converter fed PMBLDCM drive air conditioning system. Figure 10(b) shows the system has a negative gain margin of -42.6 dB and phase margin of 96.8°, which

‘ZFM-CSC converter fed PMBLDCM drive air conditioning system’ scheme.

FIGURE 10  Bode plot based stability performance comparison with conventional DC-DC converter fed system vs. proposed system, (a) Bode plot for buck boost converter fed PMBLDCM driven air conditioning system, (b) Bode plot for SEPIC converter fed PMBLDCM driven air conditioning system, (c) Bode plot for Luo converter fed PMBLDCM driven air conditioning system, (d) Bode plot for ZFM-CSC converter fed PMBLDCM driven air conditioning system

(a) Bode plot for buck boost converter fed PMBLDCM driven air conditioning system

(b) Bode plot for SEPIC converter fed PMBLDCM driven air conditioning system

(c) Bode plot for Luo converter fed PMBLDCM driven air conditioning system

(d) Bode plot for ZFM-CSC converter fed PMBLDCM driven air conditioning system
makes the system unreliable due to the unstable response. Figure 10(b) presents the stability performance during a conventional SEPIC converter fed PMBLDCM drive air conditioning system.

Figure 10(b) shows that the frequency response of the SEPIC converter based conventional system has a negative gain margin of -50.8 dB and phase margin of 8.07°, which makes system unstable under this condition. Figure 10(c) presents the stability performance of the conventional Luo converter fed PMBLDCM drive air conditioning system for remote locations.

Figure 10(c) shows that the system has infinite gain margin and phase margin 0.925°, which makes this system unstable as the system oscillates due to low phase margin. Figure 10(d) presents the stability performance of proposed ZFM-CSC converter fed PMBLDCM air conditioning system for remote and hilly areas.

Figure 10(d) shows that the frequency response of proposed scheme has infinite gain margin and phase margin 91.6°, which is good in respect of stability thus the system is stable during the operation.

The system performance given in Figure 10(a–d), shows that proposed ‘ZFM-CSC based PMBLDCM air conditioning system’ has significantly better stability in comparison to the other conventional schemes, such that buck-boost, SEPIC and Luo converter fed PMBLDCM drive air conditioning system for remote and hilly areas.

7 | CONCLUSIONS

A power factor corrected (PFC) sliding mode feedback controlled modified CSC-PMBLDCM drive for standalone generator fed PMBLDCM fed air conditioning system has been successfully mathematically modelled and simulated on MATLAB platform. Simulated results presented here, prove the significant improvement in steady state and dynamic performance of a PMBLDCM drive system. The experimental and simulated results of proposed scheme prove the robustness of proposed system. The THD in source current is less than 5%, therefore, proposed scheme meets the IEEE:519 standard of power quality. The proposed scheme is designed using an adaptive sliding mode feedback control, which removes all possibilities of over- shoot and undershoot in the DC link voltage to improve the reliability of the system and life of the power electronic switch. It also reduces required voltage rating of the power electronics switch (IGBTs) and voltage rating of the DC link capacitor of VSI. The proposed scheme is found suitable for the PMBLDCM fed air conditioning system, which are being fed by the power generation sources with poor frequency regulation. All possibilities of fluctuation/oscillations/overshoot in the speed of PMBLDCM fed air conditioning system are also removed during the starting period and at load perturbation conditions.

NOMENCLATURE

| Symbol | Quantity |
|--------|----------|
| C1     | Converter’s transfer capacitor |
| Caux   | Auxilary winding capacitance |
| C0     | Converter’s output capacitor |
| Csh    | Shunt winding capacitance |
| D      | Duty cycle |
| D1     | Converter’s diode |
| gsw1   | Gate signal to converter switch Sw1 |
| H1-H3  | Hall position sensor signal |
| ipR    | Reference value of rectified current |
| iS     | Source current |
| iD     | DC link current |
| iR     | Rectified source current |
| ire    | Error in rectified current |
| l1     | Converter’s inductor |
| l0     | Converter’s output inductor |
| uD1    | VSC Switches |
| uR1    | Converter switch |

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### APPENDIX

#### System Parameters

**A. Parameters of Single-phase SEAG, 3.7 kW, 230 V, 50 Hz, 4-Pole SEIG, RM= 0.8 Ω, X/M = 0.47 Ω, R,A = 1.3 Ω, X/Δ = 1.64 Ω, \( R_p = 0.91 \Omega, X_{fr} = 1.39 \Omega \) and auxiliary to main winding turns ratio \( N_A/N_M = 1.4 \).**

**B. Prime Mover**

A three-phase, 7.5 kW, 415 V, Δ-connected, 4-pole induction motor fed from a variable frequency drive has been used as prime mover.

**C. \( P^M\text{BLDCM} \) Motor Parameters**

| Number of Poles | Rated Power \( (P_{\text{rated}}) \) | Rev. Speed \( (N_{\text{rated}}) \) | Voltage Constant \( (K_V) \) | Torque Constant \( (K_T) \) | Phase Resistance \( (R_p) \) | \( K_p \) Per Phase Inductance \( (L_p) \) | Moment of Inertia \( (J) \) | \( 1.2 \times 10^{-3} \text{N.m.} \) |
|-----------------|--------------------------------------|-----------------|---------|-----------------|----------------|-----------------|-----------------|-----------------|
| 4               | 750 W                                 | 4000 R/M        | 84 V/kRPM | 0.83 Nm A^{-1} | 18.56 Ω       | 2315–2322 (2016) | 3 × 10^{-3} N.m. | 1.2 × 10^{-3} N.m. |

#### DC-DC Converter Parameters

| \( L_f \) | \( C_f \) | \( I_{\text{load}} \) | \( C_{\text{aux}} \) | \( \delta_{\text{aux}} \) | \( D_f \) | \( D_{\text{aux}} \) |
|----------|----------|-----------------|-----------------|-----------------|----------|----------|
| 4 m H    | 0.66 μF  | 3 m H           | 2200 μF         | SKM100GB12T4    | \( \delta_{\text{aux}} \) | SKM100GB12T4 |