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Renewable Energy Fed Pumping Motor Drive Using Modified Buck Converter

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Abstract

The widespread adoption of renewable energy resources has prompted to modify the existing systems, resulting it to be environmentally friendly and cost-effective with enhanced performance. This paper deals a water pumping system equipped with a battery back-up using an integrated charging system wherein, a modified DC-DC (buck) converter has been proposed for reliable operation. Proposed converter topology uses a minimal component count offering a variation of DC link voltage in a wide range (buck operation). Further, in the system, a three-phase induction motor is used as a pumping motor whose drive unit has been operated by employing the concept of indirect field oriented control (FOC) for enhanced performance. Developed system has been operated and investigated by using the simulation platform of Matlab/Simulink. It has been found that the magnitude of harmonics in the output of proposed converter topology is relatively low resulting in smaller switching losses. Hence, the diminished harmonic effect leads to an improved efficiency of the system using the proposed converter.

Keywords: Buck converter; Pumping system; Integrated charger

1. Introduction

In view of the increasing demand of energy together with the environmental concerns, renewable source of energy has been used extensively in the operation of most system. In this regard, solar PV power is considered as a most preferable choice whose availability is endless [1]. This has provided an opportunity to supply all types of loads which may be critical in nature. For last few decades, many research works were conducted to provide an efficient and robust system suited for critical loads particularly, water pumping system in rural area [2-4]. With the advancement in power electronics field, both DC and AC drives may be used for pumping operation system. DC motor is preferably used for lower power application due to simplicity in control with high performance [5-7]. But the frequent maintenance due to the use of commutator and brushes results in high operation cost. To deal with such issues, brushless DC motor are now preferably used with renewable energy with pumping system [8] wherein, a power factor corrected (PFC) boost converter were used and power sharing based on climatic change has been presented with enhanced reliability. In such system, maintenance free operation is obtained with improved performance with lower operational cost [9]. However, to ensure the robustness in higher power applications, induction motor is preferably used in water pumping system. Higher performance is ensured by using the concept of field oriented control to achieve the characteristic similar to DC motor [1-16].

Together with use of renewable energy in pumping application, research focus is presently on the inclusion of an additional battery backup to ensure higher reliability of the system with advanced technique [17]. In this regard, only limited literatures are available. Together with the battery backup, solar PV in two stages was used to drive induction motor in pumping system [1]. Problem of uncertainty in power generation due to change in environmental conditions and solar isolation was addressed by using an additional battery backup which is also suitable for a fast dynamic response of the system. Authors [19] have used a switched reluctance motor (SRM) in pumping system backup with a battery with single pulse mode. It was claimed that pumping system become more efficient and reliable. Analysis has been extended [20] and concluded that an optimized energy can be achieved at relatively lower frequency range (around 37 Hz.) with variable speed drives (VFDs).

Further instead of using one input source, two (or more) inputs may be used to increase the reliability of pumping system. In this regard, several designs configuration for hybrid water pumping systems have been proposed in the past, primarily incorporating solar power along with other renewable energy sources. One such hybrid design of a wind-solar PV was suggested for remote areas [21] in which a battery backup was employed in the region particularly, Riyadh, Guriat, Dhahran and Jeddah. In the design, solar panels may be operated in off-grid mode with wind turbine [22-23] or fuel cells [24] wherein, an isolated MPPT control scheme was employed. For the operation at maximum power, hybrid system of solar-fuel cell was reported to use fuzzy logic in the MPPT method [25].

This paper presents a pumping system powered by the suitable renewable energy source to drive a pumping motor through the proposed DC-DC (buck) converter. A control technique has been developed for DC-link regulation for an effective battery charging during plug-in operation. In the system, a three-phase induction machine is used as a pumping motor wherein, the higher performance is ensured by employing an advanced indirect field-oriented control (FOC). Complete developed system has been analytically

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investigated in Matlab/Simulink environment. Remaining sections of the paper are arranged as follows: Section 2 presents the mathematical model of pumping motor. Both plug-in with proposed DC-DC (buck) converter and pumping operation have been presented in section 3. Control schemes developed for proposed converter together with indirect FOC of pumping motor have been presented in section 4. Key analytical results of complete system have been presented in section 5 together with concluding remarks in section 6.

2. Mathematical modelling of pumping motor

In the present system, a three-phase induction motor is considered to be used as pumping motor. For simpler analysis and control, motor is preferably expressed in two-axis (*DQ0*) coordinate system rotating at an auxiliary speed ω_A [14, 15]:

$$\boldsymbol{v_{QDS}} = r_S \boldsymbol{i_{QDS}} + \omega_A \boldsymbol{\emptyset_{DQS}} + p\boldsymbol{\emptyset_{QDS}} \quad (1)$$

$$\boldsymbol{v_{QDR}} = r_R \boldsymbol{i_{QDR}} + (\omega_A - \omega_R)\boldsymbol{\emptyset_{DQS}} + p\boldsymbol{\emptyset_{QDR}} \quad (2)$$

In above equations, quantity (i.e. voltage v, current i and field flux $\emptyset$) with subscript '*S*' and '*R*' is associated with stator and rotor circuit respectively. Also,

$$\boldsymbol{v_{QDS}} = \left[v_{QS}\ v_{DS}\right]^T;\ \boldsymbol{v_{QDR}} = \left[v_{QR}\ v_{DR}\right]^T;\ \boldsymbol{i_{QDS}} = \left[i_{QS}\ i_{DS}\right]^T;\ \boldsymbol{i_{QDR}} = \left[i_{QR}\ i_{DR}\right]^T;$$

$$\boldsymbol{\emptyset_{QDS}} = \left[\emptyset_{QS}\ \emptyset_{DS}\right]^T;\quad \boldsymbol{\emptyset_{QDR}} = \left[\emptyset_{QR}\ \emptyset_{DR}\right]^T;\quad \boldsymbol{\emptyset_{DQS}} = \left[\emptyset_{DS}\ -\emptyset_{QS}\right]^T;\ \boldsymbol{\emptyset_{DQR}} = \left[\emptyset_{DR}\ -\emptyset_{QR}\right]^T$$

The two-axis current (i_{QDS} and i_{QDR}) and field flux ($\emptyset_{DQS}$ and $\emptyset_{QDR}$) are defined as

$$\boldsymbol{\emptyset_{DQS}} = L_{lS}\boldsymbol{i_{DQS}} + L_M\left(\boldsymbol{i_{DQS}} + \boldsymbol{i_{DQR}}\right) \quad (3)$$

$$\boldsymbol{\emptyset_{DQR}} = L_{lR}\boldsymbol{i_{DQR}} + L_M\left(\boldsymbol{i_{DQS}} + \boldsymbol{i_{DQR}}\right) \quad (4)$$

Rotor dynamics are defined as

$$\tau_E = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\emptyset_{DS} i_{QS} - \emptyset_{QS} i_{DS}\right) \quad (5)$$

$$\omega_R = \left(\frac{P}{2}\right)\int(\tau_E - \tau_L)dt \quad (6)$$

where in above equations, symbols are defined as
r_S: Stator winding resistance per phase.
r_R: Rotor winding resistance per phase.
L_{lS}: Leakage inductance of stator winding.
L_{lR}: Leakage inductance of rotor winding.
L_M: Mutual inductance between stator and rotor winding.
P: Number of poles.
τ_E: Motor torque.
τ_L: Load torque
ω_R: Rotor speed.

3. Modified buck converter operation

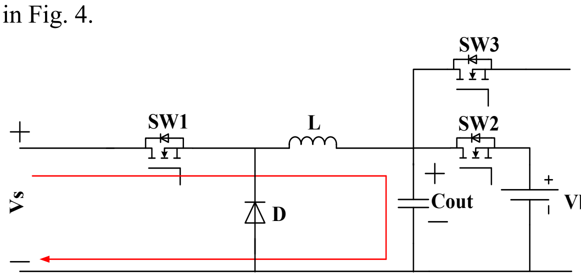
The DC input to the proposed converter is fed from any suitable renewable energy source in single or hybrid combination (like solar and/or fuel cell etc.) hence, designated as converter on renewable energy side (CRES). Proposed modified buck converter i.e. CRES is constituted by smaller number of components: three power electronic switches $SW1$, $SW2$, $SW3$, single diode, smoothening inductor (L) and output capacitor (C_{out}), shown in Fig. 1. In the considered water pumped system, proposed CRES operates in the following modes:

3.1 Plug-in mode

In this mode, charging of the connected battery takes place through the proposed buck converter. At stage I, switch $SW1$ is in ON position (i.e. $SW1 = 1$) and current will flow through the path: $V_S^+ - SW1 - L - C_{out}^+ - C_{out}^- - V_S^-$. Hence, the energy is transfermed from source (V_S) to the inductor (L). Further in stage II, switch $SW1$ is in OFF position (i.e. $SW1 = 0$) and flow of current will follow the path: $L - C_{out}^+ - C_{out}^- - D$ hence, stored energy of inductor (L) will propagate to output capacitor (C_{out}) resulting the voltage v_{Cout} to increase. With the voltage build-up of capacitor, current i_L will start to decrease. The stored energy of output capacitor C_{out} will then transferred to the connected battery. Hence in stage III, with ON position of switch $SW2$ i.e. $SW2 = 1$, charging of the battery will take place, resulting in the increase in both voltage V_{bout} and current I_{bout}. Current path in stage I, stage II and stage III is shown in Fig. 1 (a), Fig. 1 (b) and Fig. 1 (c) respectively. Associated current and voltage waveform under plug-in mode is shown in Fig. 3 (a).

3.2 Pumping operation

During this mode, the stored energy in battery through the output capacitor is transferred to induction motor drive (IMD) system for water pumping operation. For this purpose, during stage I, switch $SW3$ is operated (i.e. $SW3 = 1$ and $SW2 = 0$) and current flows through the path: $C_{out}^+ - SW3 - IMD - C_{out}^-$. This will result in the discharging of capacitor and hence decrease in the voltage v_{Cout}. So to continue with the operation of IMD, required minimum voltage (V_{min}) is maintained to the output capacitor such that, $v_{Cout} \le V_{min}$. Hence in stage II, switch $SW2$ is in ON position (i.e. $SW2 = 1$ and $SW3 = 0$) resulting in the current circulation through the path: $V_{bout}^+ - SW2 - C_{out}^+ - C_{out}^- - V_{bout}^-$. This results in the decrease of both battery voltage V_{bout} and current I_{bout} resulting in the transfer of stored to capacitor C_{out}. Current path in stage I and stage II is shown in Fig. 2 (a) and Fig. 2 (b) respectively. Associated current and voltage waveform under pumping operation is shown in Fig. 3 (b). A simplified operation of proposed DC-DC (buck) converter in during plug-in and pumping operation has been shown in the form of flow chart in Fig. 4.



(a)

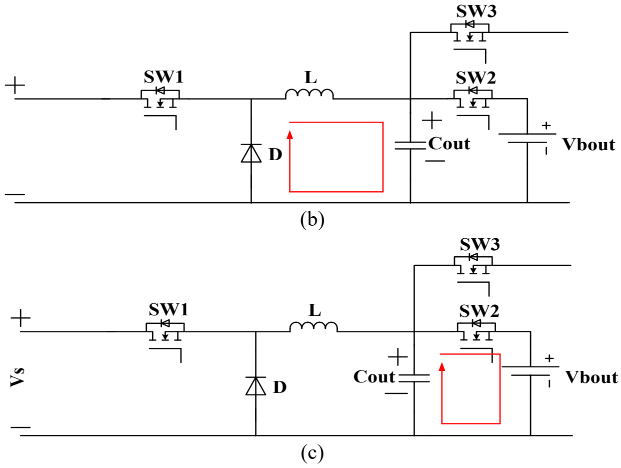


Fig. 1. Plug-in operation of the system

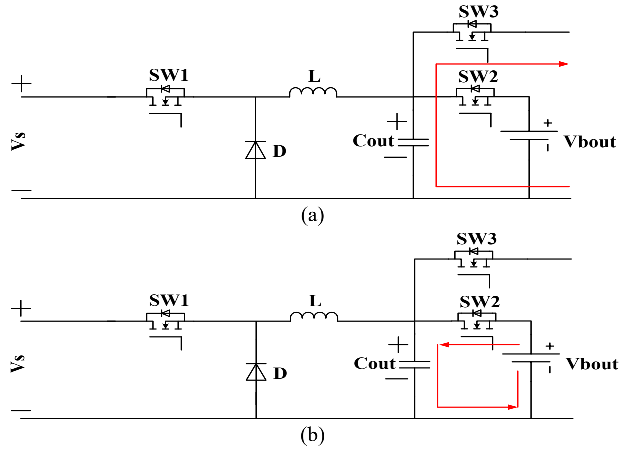


Fig. 2. Pumping operation of system

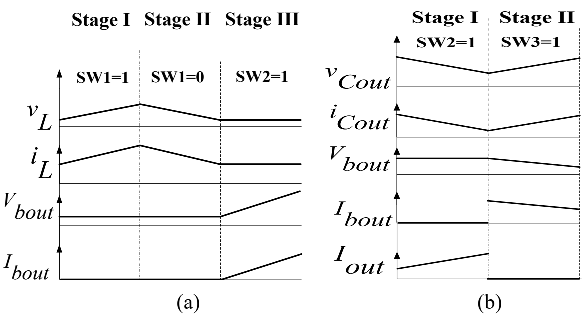


Fig. 3. Voltage-current (a) plug-in (b) pumping operation

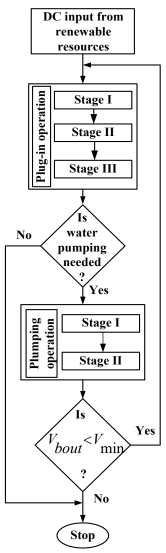


Fig. 4. Flow chart of the operation with proposed converter

4. Control schemes of proposed pumping system

Complete water pumping system is shown in Fig. 5 wherein, modified buck converter is connected to three-phase IMD unit. Employed control techniques in pumping system are given below:

4.1 CRES control

During plug-in operation, DC link voltage V_{DC} is compared to its reference value V_{DC}^* and voltage error is fed to a proportional-integral (PI) controller G_{1C} to obtain the duty cycle of the converter. Output of G_{1C} is further processed with the carrier signal through pulse generator circuit to obtain switching signal S_1 of switch $SW1$. Further, switching signal S_2 of switch $SW2$ is obtained by logically comparing DC link voltage V_{DC} with the reference value of battery V_{bout}^* as given below:

$if\ (V_{DC} > V_{bout}^*)$
$S_2 = 1$
$else$
$S_2 = 0$
$end;$

During pumping operation, V_{bout} is compared with the reference value of DC link voltage V_{DC}^* producing voltage error, to be fed in a PI controller G_{2C} to obtain duty cycle of switch $SW2$. It is further processed through pulse generator circuit with carrier signal to obtain switching signal S_2 of switch $SW2$. Switching operation of $SW3$ is complementary to $SW2$ hence, a NOT gate is used to obtain S_3 of $SW3$.

4.2 Control of pumping motor drive

Concept of indirect FOC has been used for an enhanced performance of employed three-phase induction motor as pumping motor. In this approach, a decoupled control of field flux and motor torque is obtained along two axes (perpendicular *D-Q* axis). For this purpose, rotor field flux $\emptyset_{DR}$ and torque controlled current i_T are obtained in synchronously rotating reference frame (i.e. synchronous speed $\omega_K = \omega_E$) such that

$$\emptyset_R = \emptyset_{DR} \tag{7}$$

$$\tau_E = K i_T \tag{8}$$

Mathematical details of IFOC of three-phase pumping motor are available in [14-16]. Implementation of complete control schemes used in the pumping system is shown in Fig. 6.

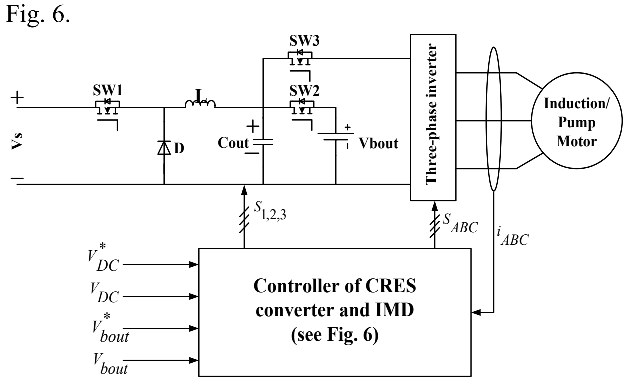


Fig. 5. Water pumping system with CRES converter and IMD unit

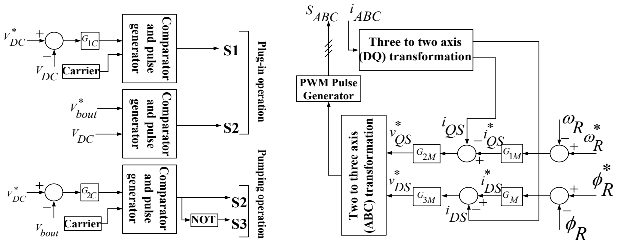


Fig. 6. Control scheme implementation in water pumping system

5. Results

Proposed buck converter has been analytically investigated wherein, input DC voltage was fed at 400 V. Input voltage may be obtained by a preferable choose of any or hybrid combination of renewable energy sources or utility grid through rectifier circuit. In the proposed converter, procedure adopted in [26] is used to calculate the parametric value of components. In the simulation, value of the inductance and capacitance used are: $L = 150\ mH$ and $C_{out} = 62.5\ \mu F$ respectively. In the converter operation, switching frequency of 20 kHz was used. Charging of the battery is initiated with SoC (state of charge) at 90 % with 300 V as nominal voltage value. In the simulation, terminal voltage of 300 V was initially fed for 3 seconds. After time $t = 3$ sec., reference voltage of 315 V is maintained to charge the battery. Changing the reference value of battery voltage is sensed to control the connected battery, as shown in Fig. 7 (a). A closed tracking capability of terminal voltage with their reference value is also shown in zoomed section of same Fig. 7 (a). Variation in the current flow of connected battery is shown in Fig. 7 (b).

In the pumping system, a three-phase induction motor having the parametric specifications shown in Table I is used as propulsion motor. Initially, pumping motor was operated at no-load. At time $t = 1.5$ sec., a 6 Nm. load torque was applied to the pumping motor which has shown a very small dip in rotor speed by 1.9 rad/sec. approximately and, regains their reference value in short duration (within 0.3 sec.). Rotor dynamic response showing the motor developed torque and speed is shown in Fig. 8 (a) and Fig. 8 (b) respectively. It may be noted that pumping motor is operated with DC input voltage fed to their inverter circuit. This input may be obtained from any source particularly, renewable energy resources or utility grid through rectifier circuit. Provision of battery back-up makes the overall system to be more reliable during supply outage or fault conditions. In such condition, battery is used to drive the pumping motor. Battery current I_B, flows through the pumping system. It may be noted that at the instant ($t = 1.5$ sec.) of the application load torque (6 Nm.) results in the increase of both battery and motor current as shown in Fig. 9 (a) and Fig. 9 (d) respectively. Only Q-axis component (i.e. active component) of motor current increases to 3.0 A approximately, with almost negligible variation in D-axis (i.e. reactive component) current as shown in Fig. 9 (b) and Fig. 9 (c) respectively. This is because, in the system motor is operated in constant torque region with constant field flux in air gap. Furthermore, variation in only active component of current signifies an effective implementation of IFOC to propulsion motor.

In the proposed system, switching signal S_1 and S_2 and, S_2 and S_3 were generated both during plug-in and pumping operation respectively. For this purpose, PI based controller G_{1C} and G_{2C} are regulated by tuning their proportional and integrator gains (i.e. K_P' and K_I' and, K_P'' and K_I'') to minimize DC link voltage error ($V_{DC}^* - V_{DC}$). Tuned values of gains used are: $K_P' = K_P'' = 6.3$ and $K_I' = K_I'' = 15.0$. On motor drive side during pumping operation, speed controller G_{1M} gains (K_{P1M}, K_{I1M}), D-Q current controller i.e., G_{2M} gains (K_{P2M}, K_{I2M}) and G_{3M} gains (K_{P3M}, K_{I3M}) were tuned to minimize error in speed ($\omega_R^* - \omega_R$) and currents (i.e. $i_{QS}^* - i_{QS}$ and $i_{DS}^* - i_{DS}$ respectively). Tuned values of gains used are: $K_{P1M} = 2.7$, $K_{I1M} = 66$ and $K_{P2M} = K_{P3M} = 580$, $K_{I2M} = K_{I3M} = 50$.

Further with respect to other topology for buck operation [27-29], proposed DC-DC (buck) converter is compared as shown in Table II. Proposed converter is relatively simpler and cost effective due to the lower number of used components. It is worth noting that the magnitude of harmonics in the converter output voltage is relatively lower compared to its conventional topology, as illustrated in Fig. 10 (a) and Fig. 10 (b), respectively. However, a relatively higher frequency ripple was observed in the battery voltage waveform. The reduction in voltage harmonic magnitude enhances the lifespan of the components and the connected battery by minimizing switching losses and mitigating the impact of ripples and harmonics to a much greater extent. Consequently, the diminished harmonic effect leads to an improved efficiency of the system using the proposed converter.

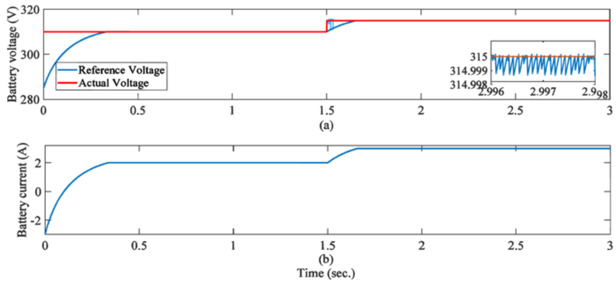


Fig. 7. Voltage-current of battery during plug-in operation showing (a) V_B (b) I_B

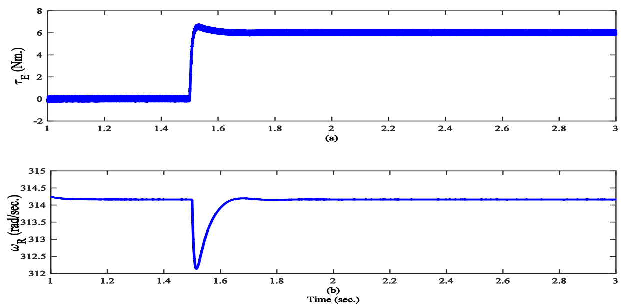


Fig. 8. Rotor dynamics (a) torque developed (b) rotor speed

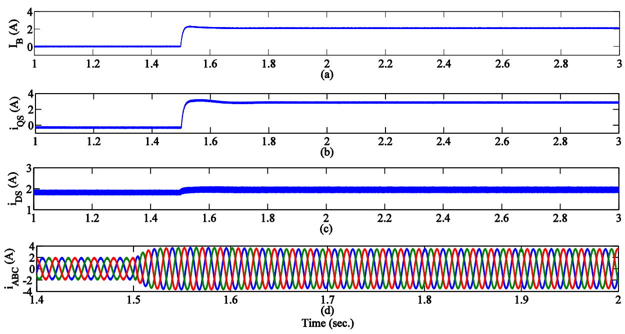


Fig. 9. Current flow in pumping system (a) battery current (b) Q-axis motor current (c) D-axis motor current (d) terminal current

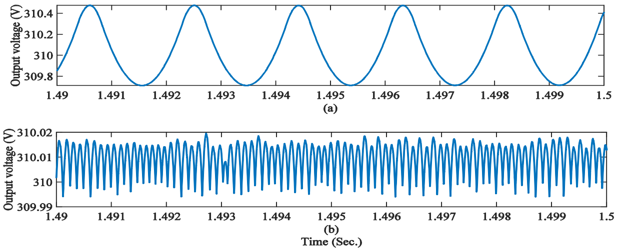


Fig. 10. Output voltage of buck converter using topology (a) conventional (b) proposed

Table 1. Propulsion motor specifications

Resistances	$r_S = 10\,\Omega$	$r_R = 6.3\,\Omega$
Inductances	$L_{LS} = 40\,mH$ $L_{LS} = 40\,mH$	$L_{LR} =$ $40\,mH$
Moment of inertia	$J = 0.03\,Kgm^2$	

Table 2. Comparison of components used in converter in charging unit

References	**Number of component**			
	Switches (S)	**Inductor (L)**	**Capacitor (C)**	**Diode (D)**
[27]	1	2	2	2
[28]	2	2	2	4
[29]	2	2	2	3
Proposed	2	1	1	1

6. Conclusion

This paper proposes a simple converter in pumping system using a battery backup. For this purpose, a simple and modified buck converter has been proposed, suitable for charging of a battery, applicable to a water pumping system. Use of a battery backup makes the system more reliable by ensuring the continuity of power supply even in the case of input DC outage or fault condition. The proposed system is capable to operate with any DC input preferably with renewable energy resources or utility grid through rectifier circuit. In the system, use of an advanced IFOC further ensures the higher performance of pumping motor through a decoupled control of field flux and torque.

In the proposed DC-DC buck converter, it has been found that the magnitude of harmonics in the output of proposed converter topology is relatively low resulting in smaller switching losses. Hence, the diminished harmonic effect leads to an improved efficiency of the system using the proposed converter.

The present work may be extended and investigated with the input supply with a possible hybrid combination of renewable energy resources. Further, control of the proposed DC-DC (buck) converter may be further improved by using the advanced mechanism particularly, artificial neural network (ANN), sliding mode, model predictive control etc.

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