A Bridgeless LUO Converter with Glowworm Swarm Optimized Tuned PI Controller for Electrical Applications

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1. Introduction

The synchronous reluctance motor (Sync-RM) is known for its higher reliability, faster dynamic response, higher efficiency, higher speed range, higher power density, and higher torque per ampere. Consequently, the scope of research into emerging Sync-RMs drive system has been extended. For different kinds of mechanical and electrical applications, motors are important components of any machine or tool. There are several types of motors available for various kinds of industrial applications, but the benefits of Sync-RM in medium- and low-power applications have eventually been very efficient compared to other motor types, regarding the factors such as high flux density per unit volume, high efficiency, requirements of low maintenance, and low electromagnetic obstruction. This research proposed a Sync-RM drive fed by a bridgeless LUO converter (BLLC) using the Glowworm Swarm Optimization (GSO) tuned proportional integral (PI) controller. High competence, higher power density, and a small structure of the motor drive are delivered by the PI-tuned converter. The output voltages are related to the Sync-RM motor of the proposed converter. Due to its minimum effort and modest development, the Sync-RM here is chosen for the drive. The proposed Sync-RM drive framework based on the LUO converter was evaluated by simulation using the Matlab/Simulink tool.

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1. Introduction

The term “Synchronous Reluctance Motor” implies a synchronous speed of rotation. In variable speed applications, it is a significant match to the induction motor. The Sync-RM is absolutely free of magnets and their problems with operation [1]. It is economical to manufacture and can run at extremely high speeds and higher temperatures than motors with a permanent magnet (PM). Its power factor and performance, however, are not as high as those of a PM motor and the requirement for the converter kVA is higher. It can work from basically normal PWM AC inverters and has a lower ripple of torque [2]. The synchronous PM motor functions as a Sync-RM; the magnets are left out or demagnetized; that is, there is no field winding or permanent magnet on the rotor for the Sync-RM. There are salient poles in the rotor, but there are flat, scattered poles in the stator. Low cost, robust, and high efficient (ideally no rotor loss) Sync-RMs are capable of working at very high speeds at higher temperatures than PM motors [3].

For low-power equipment such as IEC 61000-3-2, the PFC converter offers the power factor based on power quality requirements. In addition, the new formation decreases the THD input current that improves the present correction factor [4]. To operate the PFC converters, continuous conduction mode (CCM), critical conduction mode (CRM), and discontinuous conduction mode (DCM) are the three working modes explored. Low input current surge and decreased electromagnetic interference (EMI) are given by the consistent inductor current in CCM. As the inductor current remains constant in the switching time frame, electromagnetic interference encounters hard switching [5, 6].
The LUO converter is widely utilized due to the voltage contains inherent qualities such as lift, ultra-lift, and super-lift, which are all useful in the conversion process. For example, the super-lift converter was considered to be remarkable since the voltage switch gain is larger than that of the other converters. This proposed structure was hence taken by the single-phase power source, which was followed by a filter, and a BLLC, which transforms it into a Sync-RM motor drive. The BLLC is regarded as the precontroller with the in-built power factors that is used in conjunction with the DICM (discontinuous inductor current mode). Controlling the speed of the Sync-RM motor to a substantial extent can be accomplished by varying the DC link voltage of the proposed LUO converter. The Sync-RM is powered by direct current derived from a BLLC, which serves as a PFC rectifier and was sustained by the single-phase alternating current. There are two components to the proposed PFC BLLC. This converter was divided into the operations between supply voltage’s negative and positive half-cycles, as well as the complete switching cycles.

PFC converters achieve zero power switch current and, for the diode, zero current in CRM operation. Although the negative label related to CRM is the switching frequency fluctuating through a broad range, resulting in a decrease in efficiency and complexity in the outline of the electromagnetic field (EMF) channel [6], the transformation techniques are easily established in the end, and there are many divisions for DC-DC converters. Since the voltage has its intrinsic qualities such as the ultra-lift, super-lift, and lift, an LUO converter is commonly used. The super-lift LUO converter was remarkably dependent, among other things, on the fact that the gain of the voltage switch was high [7, 8]. In the electronic circuit strategy, the voltage lift (VL) method is widely used.

The super-lift (SL) technique, along with enhancing the transformation mechanism, was more efficient than the VL system. For controlling the stator windings sequence, Sync-RM requires energy converters. Generally, at each point, Sync-RM converters have two switches. These Sync-RM current waveforms are very flexible and compulsive controls [9]. Additionally, the circuit of the converter contains a passive low-pass LC filter. An alteration in the DPF (distortion power factor) is given by the LC passive filters, as the design of the filter capacitor was created to provide the appropriate phase to switch to PFC. In the meantime, without considering the supply-side details, this passive filter also for the switching harmonic provides low impedance.

2. Related Works

Due to the high output power, low cost, and durability in different industry applications, Sync-RMs has received a lot of attention [9]. Sync-RM may replace the induction, switched reluctance, and permanent magnet motors that are most widely used. In the performance, torque, and power density, Sync-RM has been shown to outperform similarly dimensioned induction motors. Due to the inclination of the salient rotor poles to harmonize with them with the synchronously rotating field produced by the stator, the motor-driven torque was generated by reluctance. The magnets were left out of the rotor in this motor, or they were demagnetized. There are salient poles in the rotor of a Sync-RM, but neither field windings nor PMs.

The Sync-RM is based on the reluctance torque principle. A spatial sinusoidal distributed magneto-motive force (MMF) was produced by the stator windings. Because of the configuration that generated a nonisotropic magnetic reluctance that interacted with the stator MMF [1], the rotor saliency generated the rotor torque. Cage less and line-start were the main types of Sync-RMs. The other two kinds were radial type and axial type, depending on the magnetization (when the stator winding was energized). The brushless DC motor drive, which was supplied by a BLLC power-factor-correction (PFC) converter, was controlled by a single voltage sensor, which also controlled the BLDC motor speed and PFC on the alternating current supply [5, 6]. The Sync-RM’s output depends primarily on the magnetizing inductance values of the d and q-axis. Sync-RM’s saliency ratio determined the power factor, parameter variance sensitivity, and field-weakening efficiency of the motor. In particular, about half of the saliency ratio was the ideal constant-power speed range. Hence, for achieving a 4:1 stable power range, theoretically, the saliency rate of at least 8 was needed [3]. A technique based on finite element simulation of the magnetic field was used to improve the Sync-RM architecture [2]. Based on the cascaded field-oriented vector control (FOC), the classical Sync-RM control technique was proposed. The Sync-RM exhibited substantial nonlinearity in magnetic saturation despite numerous advantages, rendering its power-optimal and ideally sensor less FOC complicated [10].

If the source was acquired from single-phase or three-phase AC transmission, the source current presents rich harmonics. Comprehensive research was made and continues to enhance the generated torque efficiency and source current’s efficiency when power was used from the AC supply [11]. Analysis in specific primary direction would analyze the different potential of utilizing new design tools, such as the analysis of finite elements or the use of various other software tools for the electromagnetic design, which can result in enhanced torque development abilities with minimum torque ripple [12]. The pole face structuring was also addressed a potential technique to increase the efficiency of torque. The other line of research was to discover the options of new circuit topologies to drive the Sync-RM, and this line of research has also delivered substantial several topological changes that typically occur with the form of accessible sources such as DC sources from rectifiers, renewable sources such as solar panels, sources of fuel cells, and batteries [10]. The Sync-RM could be tried with uncontrolled and controlled rectifiers trailed with the DC-DC converter of a general kind or latest converters such as SEPIC, CUK, or LUO. Another alternative was the matrix converter if the source was a multiphase form AC. The development of different control schemes was the other direction of research [7].

For convenience, the PI speed controller parameters and the initial EKF covariance matrix value were tuned off using
PSO (particle swarm optimization) in [12]. Newly built prototypes of Sync-RMs provide an alternative to the reference induction motors shown in [13]. Since rotor losses are reduced, Sync-RM has slight high efficiency over IM. Low-power variables were the key downside of Sync-RM. There was no need for field excitation at zero torque in this motor; hence, the losses of electromagnetic spinning were removed. Demagnetization was not a concern; Sync-RMs were, therefore, generally more efficient than permanent magnet motors.

Using multipurpose feature, a smart controller for speed regulation of the BLDC drive system was presented in [14]. It was decided to employ a fractional order PID controller based on a modified LUO converter in order to eliminate the torque ripples and manage the BLDC motor speed in this case. With the hybrid technique, the researchers were able to synthesize an improved LUO converter that was on the basis of ANFIS as well as elephant herding optimization. To begin, the optimization technique was examined in order to determine the error function. ANFIS controllers are also efficient since they are built using a method that is systematic in its tracking of error function to deliver the greatest possible gain values optimal. The control method used to decrease harmonics and torque ripples was successful.

The use of a bridgeless power factors adjusted LUO converter allows the switched reluctance motor to be driven directly from the utility alternating current supply. It was, therefore, appropriate for a wide range of home applications due to this. The usage of a sliding mode controller helps to improve the control over speed management. For achieving the appropriate speed, the front-end BLLC and the drive systems could both be controlled. Various configurations of the modulation index and duty cycle are possible, allowing the system to be versatile in order to fulfill different demands while maintaining a low steady-state error rate [15].

A hybrid renewable energy source that was incorporated into the grid was proposed in [16]. The LUO converter, which was controlled by an optimized PI controller, was employed to maintain a steady DC link voltage. The voltage was raised with the help of a LUO converter, and the raised voltage was regulated by an optimized PI controller, which was implemented. The optimization process was carried out with the support of the ABC optimization. Because of this optimization approach, it was possible to keep the power fluctuation in a steady-state mode. It was a straightforward and dependable approach for doing optimization effectively.

3. Proposed Methodology

The proposed Sync-RM drive system based on the BLLC block diagram is shown in Figure 1. After the filter, a single-phase supply then adopts this proposed model, and BLLC converts to a Sync-RM motor drive. The BLLC converter was held to be an in-built power factor precontroller for DICM (discontinuous inductor current mode) operation. The Sync-RM motor’s speed is significantly controlled by switching the DC link voltage of the proposed LUO converter.

The Sync-RM is operated by DC power attracted from a BLLC converter used from AC single-phase utility power supply as a PFC rectifier. In the following sections, the delicate elements of the BLLC-based PFC rectifier are presented.

3.1. PFC BLLC Converter. The PFC BLLC was divided into two parts that integrate the task into the supply voltage’s negative and positive half-cycles and the complete switching period. The circuit diagram of the proposed BL-LUO Converter is shown in Figure 2.

3.2. Operation Modes in BLLC Converter. The PFC function of the BLLC switch between the supply voltage’s positive half-cycle and the complete switching time is shown in Figures 3–5.

3.2.1. Mode I. As shown in Figure 6, the inductor on the input side (i_L1) saves energy according to the current passage (i_{l1}) through it, and (i_{L1}) is the inductor when the switch SW_{1} is triggered. In addition, at the direct current side capacitor (C_{d}) and an output side inductor (L_{o}), the energy contained in a transition capacitor (C_{1}) was transformed. The median transverse capacitor (V_{C1}) voltage, therefore, minimizes when the DC interface voltage (V_{dc}) and the output inductance (i_{L0}) current are extended.

3.2.2. Mode II. As shown in Figure 7, the inductor at input side (L_{o1}) switches its energy to the capacitor (C_{1}) over diode D_{p1} when SW_{1} has been switched off. The current i_{L1} decreases until it reaches 0, while the voltage increases across the centre of the middle capacitor (V_{C1}). C_{d} provides the load with the energy required. Therefore, in this method of operation, DC link voltage V_{dc} decreases.

3.2.3. Mode III. As it is seen in Figure 8, in the input inductor (L_{o1}), no energy was left, i.e., the i_{L2}C current ends at 0 and enters the DCM operation. The capacitor C_{1}, and the output inductance (L_{o1}) were released; thus, when DC voltage link V_{dc} increase in this task appears in the fig, the V_{C1} voltage current of i_{L0} are decreased. When the SW_{1} switch has been returned, the task is repeated.

Similarly, to achieve the desired operation, the supply voltage’s negative half-cycle L_{L2} and L_{o2} of the inductor, intermediate D_{n1}, and capacitor diode C_{2} were conducted.

3.3. Zeigler Nicholas Approach for PI Controller Tuning. The initial technique of tuning the PI controller by Zeigler Nicholas (ZN) is additionally called as the method of the reaction curve. Both the elements a and b are obtained from the reaction curve obtained, and from these both elements and by utilizing an empirical law, Ki and Kp values are obtained. The Sync-RM speed is an operating voltage function for given load torque, and the DC link operating voltage could be controlled by regulating the duty cycle...
utilized in the PWM drive system to consecutively energize Sync-RM phases [17].

The DC link voltage hence turns out as the regulated variable, and the manipulated variable turns out as the duty cycle. A transfer function (TF) was obtained to outline the reaction curve among the duty cycle and DC link voltage. In (1), the TF of the approximate model PFC-LUO converter was presented. It estimates the TF among the duty cycle and the voltage of the DC link:

\[
\text{DC link Voltage} = 1.746e^{0.5} s + 4.542e^{0.8}. \tag{1}
\]

To obtain the reaction curve, the transfer function is used. With the change of step from 0 to 0.5, the reaction curve was acquired by adding a step input.

The ZN tuning approach is a conventional method, where the reaction was initially drawn. The curve has a concave section accompanied by a convex section, starting
from the origin. In the reaction curve, the transition point from the concave section to the convex section is called the point of inflection. By extending the steady-state level according to Figure 9, the acquired values for $K_i$ and $K_p$ and a tangent were plotted through the inflection point, and this tangent obstructs the $y$-axis and $x$-axis and the line plotted to the $y$-axis.

### 3.4. GSO-Based PI Controller Tuning

By the idea of glowworms foraging or courtship behavior, which glows to attract companions, the GSO algorithm was developed. In GSO, every glowworm has a particular amount of luciferin that defines the intensity of the luminance [18]. Glowworms operate using an algorithm that causes them to seek out their brightest neighbor. Using just local data, the swarm may be separated into several subgroups that intersect via various optimums to a multimodal function, which is the result of these activities. GSO consists of four main stages: distribution, luciferin update, movement, and neighborhood range update. Controlling the performance index is the primary goal of this basic PI tuning approach. For example, the integral square error (ISE) was the objective function’s output index that is framed to minimize the ISE. Each of the glowworms solution vectors will be modified at the end of each iteration [19–21].

#### 3.5. Glowworm Distribute Stage

Randomly dispersed $n$ glowworms are placed at various points in the search space. Every glowworm carries the same quantity of luciferin.

#### 3.5.1. Luciferin Update Stage

The update process for luciferin is according to the objective function’s value and the past level of individual luciferin. The luciferin update rule is

$$l_g(i) = (1 - \rho)l_{g-1}(i) + \gamma H(x_g(i)),$$  

where $l_g(i)$ represents at the $i^{th}$ iteration the luciferin value of glowworm $g$, $\gamma$ and $\rho$, $H(x_g(i))$ is the objective function’s
value at the position of the glowworm \( g \), and \( L(x_g(i)) \) is the luciferin enhancement factor and decay.

### 3.5.2. Glowworm Movement Stage

During the movement stage, each glowworm follows a probabilistic path to a neighbor with a higher brightness than its own. The chance of a glowworm \( g \) travelling to a neighbor \( h \) is calculated as follows:

\[
P_{gh}(i) = \frac{(I_h(i) - L_g(i))}{\sum_{j \in N_g(i)}(I_j(i) - L_g(i))},
\]

where \( h \in N_g(i) \); \( N_g(i) \) is a set that could be verified by

\[
h \in N_g(i), N_g(i) = \{h: d_{gh}(i) < r_g(i) \},
\]

where \( d_{gh}(i) \) represents the Euclidean distance within glowworm \( g \) and \( h \) at the iteration of \( i \) and \( r_g(i) \) represents the variable neighborhood range at the iteration of \( i \) related to glowworm \( g \). Then, the movement model for the glowworm is

\[
x_{g}(i + 1) = x_{g}(i) + s_i \cdot (x_{h}(i) - x_{g}(i)),
\]

Where \( x_g(i) \epsilon R^m \) is the glowworm \( g \) location at the \( i^{th} \) iteration in the \( m \)-dimensional real space \( R^m \), \( x_h(i) - x_g(i) \) indicates the operator of the Euclidean norm, and \( s_i(>0) \) is the step’s size.

### 3.5.3. Neighborhood Range Update Stage

In the following equation, each glowworm’s neighborhood domain is given, considering \( r_s \) as the first neighborhood domain for each glowworm:

\[
q_{d}^g(i + 1) = \min\{r_s, \max\{0, r_{d}^g(i) + \beta(n_i - N_g(i))\}\},
\]

where \( \beta \) is a constant, \( n_i \) is a parameter of control for the number of neighborhoods, \( r_s \) represents a glowworm’s sensory radius, and \( N_g(i) \) represents neighborhoods set [22–28].

The two random numbers are utilized along with this simple GSO algorithm. In Table 1, the \( k_i \) and \( k_p \) values obtained from the ZN and the GSO technique were estimated.

### 4. Results and Discussion

For this section, the simulation based on MATLAB SIMULINK and the setup was designed around a Sync-RM of 2.2 kW (4 pole) motor.

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**Table 1: Evaluation of kp and ki.**

| Tuning technique | Kp   | Ki   |
|------------------|------|------|
| ZN technique     | 0.1  | 1.3  |
| PSO technique    | 0.106| 1.38 |
| GSO technique    | 0.125| 1.44 |

**Table 2: Performance analysis of Sync-RM.**

| Parameters   | 25% | 50% | 75% | 100% | 115% | 125% |
|--------------|-----|-----|-----|------|------|------|
| Voltage (V)  | 395.7| 435.6| 456.5| 453.4| 454.8| 449.7|
| Input_Power (W) | 652  | 1255 | 1862 | 2485 | 3129 | 3814 |
| Phase_Current (A) | 2.33 | 3.24 | 4.01 | 4.81 | 5.75 | 7.06 |
| Torque (Nm) | 3.48 | 7.01 | 10.12| 14.07| 17.53| 21.08|
| Speed (rpm) | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| Output power (W) | 551.3| 1104| 1645| 2206| 2756| 3302|
| Efficiency | 84.9 | 86.4 | 87.2 | 88.5 | 87.4 | 86.2 |

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Variable frequency drives are used in the model. The variable AC power source is fed to the inverter. During the measurement, the inverter’s input voltage is set. In the inverter’s operational menu, the power and rotational speed are adjusted to the suitable rated outcome. The inverter controls the motor’s output power and speed. Two power analyzers are employed in the prototype system for measurements. One is among the varying AC supply and inverter, while the other is among the motor and inverter. A direct calculation of electrical output of the converter, based on the motor’s input power and the output mechanical power of its shaft, is used to estimate Sync-RM efficiency. The output torque of the motor was determined using a torque sensor. The IEC 60034-2-3 loads test is used to base the computation. At regulated speeds of 1, 25, 1, 15 and 1, 0, 75 and 0, 50, and 25 percent of the rated load, six normal operating points are carried out according to the rules. For each load, we monitor the input control, load torque, stator total current, phase-phase voltage, and speed. Table 2 displays the results of the load test.

The measurements of the parameters included both input and output measurements. These measurements are calculated at different load levels, with load level varying from 25% to 125%. Based on the load level, there is variation...
in the performance of the Sync-RM. The voltage increases constantly while the load increases; the voltage reaches to its maximum level of 449.7 V when the load is given at 125%. The phase current reaches from 2.33 A to 7.06 A. The input power was measured in watts; it varies from 652 W to 3814 W based on the load level given from 25% to 125%. The torque was measured using the sensor which ranges between 3.48 Nm and 21.08 Nm based on different load levels. The speed of the motor is measured at each load level, where the speed is set at constant speed of 1500 Rpm at each load. The output power was measured in watts, where it varies from 551 W to 3302 W. The efficiency obtained was varied for 84.9% to 88.5% (refer Figures 3–11).

5. Conclusion

To drive the 2.2 kW Sync-RM with a split DC power source, a novel PFC BLDC was developed in this research. Utilizing a Zeigler [29] Nicholas approach and GSO-based tuned PI controller, the Sync-RM speed regulation was carried out, which [30] controls the BLDC’s duty cycles and controls DC link voltage. Correlated with a standard rectifier-based drive for the Sync-RM, the primary current extracted from the AC single-phase supply showed enhanced quality of power. Using the MATLAB SIMULINK tool and experimental verification, the proposed concept was simulated and validated. The proposed GSO-based PI tuned method compared to the ZN method and PSO provided better results. Stator current and phase-phase voltage were evaluated in addition to input control and output torque during the performance evaluation.

Data Availability

No data were used to support this study.

Consent

Not Applicable.

Conflicts of Interest

The authors declare that there is no conflicts of interest.

Authors’ Contributions

Dr. M. Sivaramkrisnan and Dr. M. Siva Ramkumar are responsible for data collection and validation. Author Siva Subramanian S. is responsible for surveys and content writing and proof reading. Author Nyagong Santino David Ladu is responsible for algorithm design, development, and proofreading.

References

[1] B. L. Mbula and S. Chowdhury, “Performance improvement of synchronous reluctance motor: a review,” in Proceedings of the IEEE PES Power Africa, pp. 402–406, Accra, Ghana, June 2017.
[2] A. V. Zakharov, S. I. Malafeev, and A. L. Dudulin, “Synchronous reluctance motor: design and experimental research,” in Proceedings of the International Conference on Electrical Power Drive Systems, pp. 1–4, Novocherkassk, Russia, October 2018.
[3] L. Haataja and L. Pyrhonen, “Permanent magnet assisted synchronous reluctance motor: an alternative motor in variable speed drives,” in Energy Efficiency in Motor Driven Systems, F. Parasiliti and P. Bertoldi, Eds., pp. 101–110, Springer, Berlin, Germany, 2003.
[4] Y. Li, Y. Yang, Z. Zhu, and W. Qiang, “A feed forward compensation design in critical conduction mode boost power factor correction for low-power low total harmonic distortion,” Journal of Semiconductors, vol. 33, no. 3, 035007 pages, 2012.
[5] B. Singh, V. Bist, A. Chandra, and K. Al-Haddad, “Power quality improvement in PFC bridgeless-Luo converter fed BLDC motor drive,” in Proceedings of the IEEE Industry Applications Society Annual Meeting, Lake Buena Vista, pp. 1–8, Lake Buena Vista, FL, USA, October 2013.
[6] B. Singh, V. Bist, A. Chandra, and K. Al-Haddad, “Power factor correction in bridgeless-Luo converter fed BLDC motor drive,” IEEE Transactions on Industry Applications, vol. 51, no. 2, pp. 1179–1188, 2015.
[7] V. R. Kota and B. N. Kommula, “A modified bridgeless Luo converter for simultaneous torque ripple minimization and power factor correction in BLDC motors,” Journal of Engineering Technology, vol. 6, pp. 71–81, 2018.
[8] M. Vishvanath and R. Balamurugan, “Bidirectional Luo converter fed switched reluctance motor,” TELKOMNIKA Indonesian Journal of Electrical Engineering, vol. 12, no. 12, pp. 8120–8125, 2014.
[9] S. H. Hwang, J. M. Kim, H. V. Khang, and J. W. Ahn, “Parameter identification of a synchronous reluctance motor by using a synchronous PI current regulator at a standstill,” Journal of Power Electronics, vol. 10, no. 5, pp. 491–497, 2010.
[10] Z. Mynar, P. Vaclavek, and P. Blaha, “Synchronous reluctance motor parameter and state estimation using extended kalman filter and current derivative measurement,” IEEE Transactions on Industrial Electronics, vol. 68, no. 3, pp. 1972–1981, 2021.
[11] J. Soltani and H. A. Zarchi, “Robust control of encoderless synchronous reluctance motor drives based on adaptive backstepping and input-output feedback linearization techniques,” International Journal of Electrical and Electronics Engineering, vol. 43, no. 1, pp. 11–22, 2011.
[12] A. Farhan, M. Abdelrahem, A. Saleh, A. Shaltout, and R. Kennel, “Simplified sensorless current predictive control of synchronous reluctance motor using online parameter estimation,” Energies, vol. 13, no. 2, p. 492, 2020.
