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Luo Converter and Hysteresis-Controlled Three-Phase Inverter for Solar PV Array-Powered BLDC Motor-Driven Water Pump

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Abstract: *This article delves into the intricacies of a solar-powered water pump employing a three-phase inverter coupled with a Brushless DC (BLDC) motor, utilizing hysteresis control. Solar power emerges as a remarkably efficient renewable energy source, surpassing traditional alternatives. The Luo (DC-DC) converter acts as an intermediate link between the solar PV array and the BLDC motor's soft start in this solar PV array-fed water pumping system. Opting for the Luo converter among diverse DC-DC converters optimizes the SPV array and BLDC motor performance, ensuring minimal semiconductor-switched intermediate Luo converter output ripple current and facilitating maximum power tracking (MPPT) within an infinite region. The use of Luo converters with positive outputs transforms positive input sources into positive output loads. Additionally, enhancing the efficiency of the electronically commutated brushless DC voltage source inverter involves operating it at elementary frequencies rather than higher frequencies, where switching losses are more pronounced. The MATLAB/Simulink environment is employed for comprehensive simulation and demonstration of various operational scenarios, encompassing dynamic, starting, and steady-state performances.*

Keywords—*Power flow control; Solar photovoltaic; Brushless DC motor; Luo converter; Hysterisis current control (HCC); Maximum power point Tracking (MPPT).*

I. Introduction

Existing BLDC motor driven water pumps fed by a PV array rely solely on solar PV energy due to the system's grid-isolation or standalone nature. The major drawback of solar PV generation is its intermittent nature, which makes the water pumping system unstable. When the weather is bad, water pumping is severely disrupted, and the system is underutilised because the pump isn't being used to its full potential. And when daylight isn't around (at night), the water pumps stop working. All of these drawbacks must be fixed before a dependable PV-based pumping system can be acquired.

One of the most promising alternatives to traditional energy sources for home appliances is solar photovoltaic (PV) generation [1]. With this in mind, water pumping has come to be seen as an important use of PV energy [2, 3]. Initially, water was pumped using DC motors before switching to an AC induction motor [4]. Numerous studies on electric motor drives have been conducted to boost the effectiveness and efficiency of PV fed pumping systems. Since the last decade [5], permanent magnet brushless DC (BLDC) motors have been chosen due to their many advantages, including their small size, low weight, high efficiency, high power density, lack of maintenance, long service life, and immunity to electromagnetic interference (EMI). It has been calculated that by incorporating this motor, not only can PV panels operate more efficiently and with no need for regular maintenance, but their size can also be reduced [6].

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Interfacing a PV generating unit installed for water pumping to a utility grid, these technologies have only recently come into the spotlight. The primary focus is on ensuring that water is pumped continuously at full capacity, day or night. In [7], the authors describe a solar water pumping system that is wired into the grid and equipped with an automatic power allocation system (when PV array is insufficient to power the pump). The DC bus shared by the PV array and the grid-connected inverter serves as the connection point for a water pump and controller. Since no battery storage is employed, the system's useful life is increased while maintenance and production expenses are minimised. However, the developed control only allows for one-way power flow, so any PV array output that is not used (when pumping is not necessary) cannot be sent back to the utility grid. The PV system is not being used to its full potential, and the customer is still expected to foot the bill for the electricity used.In another system, the PV energy is fed into the utility grid via an inverter, and the water pump is powered by the utility grid via an inverter. It is not immediately obvious that this is a PV pumping system connected to the utility grid. In [8], a hybrid PV water pumping system is described in which a battery is charged by a PV array through a charge controller and then discharged to supply the water pump through an inverter. A utility interface is available for the pump and can be activated via a toggle. Due to the high manufacturing and upkeep cost of the battery storage, this system becomes prohibitively expensive. In [9-10], the PV installation is split in two: some of it is used to pump water, and the rest provides electricity to the grid. Since the pumps are powered solely by PV energy and not by the utility, the system is not reliable. The remaining power is drawn from the grid as needed, and a grid-interfaced PV fed-BLDC motor driven water pumping system with unidirectional power flow control has been developed. If water pumping is not necessary, the developed system wastes PV power.All of the aforementioned conventional PV pumping system topologies feature either grid-feeding or grid-dependent power flow control. Both the PV installation and the pumping system can benefit from the development of a multipurpose system that could allow for bidirectional power flow under certain operating conditions. In this paper, a similar system is introduced for the first time using a BLDC motor drive. As stated, the proposed system is concerned with the creation of bidirectional power flow control, which allows energy to flow from the PV array to the single phase utility grid when water pumping is not needed, and vice versa when the PV array's power is insufficient (or at night) to run the pump at full capacity. Customers can generate income by selling excess electricity to the utility company, thanks to this practise. This is accomplished through the application of a unit vector template (UVT) generation, which is used because of its ease of use and suitability for the goal at hand. In [11], it is described how some of the above features can be found in a PV-based water pumping system that interfaces with the grid. This article expands upon the previous ones by including specifics on the methodology behind the design, the controls, the simulation analysis, and the hardware implementation.Using a DC-DC LUO converter and an incremental conductance (InC) method, we can track the Maximum Power Point (MPPT) of a PV array [12-16]. For a set amount of time, the VSI (Voltage Source Inverter) is put into PWM (Pulse Width Modulation) mode, which regulates the stator current of a BLDC motor during startup. But once the motor is up and running, the VSI is run on fundamental frequency pulses, reducing switching loss and improving conversion efficiency. The cost savings from using a BLDC motor is further enhanced by the fact that no phase current sensor is required for control. To prove the claims, a grid-interactive PV-based water-pumping system with a BLDC motor drive is designed, modelled, and simulated in the MATLAB/Simulink platform, with its performance then being evaluated using simulated results and, finally, hardware implementation. The following are the major results of this study:Connecting the BLDC motor-driven solar water pumping system to the grid is an important step toward creating a sustainable water pumping system.The proposed bidirectional control of power flow ensures constant water delivery at full volume

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in all climates.If the water pumping isn't needed, the surplus energy from the PV array can be sent back to the grid. This function allows for optimal use of the available hardware. In addition, the system becomes a revenue stream through the sale of electricity to the utility.In addition to ensuring uninterrupted water delivery during power outages, the proposed water pumping system is engineered and controlled to function autonomously in the event of such a scenario. As a result, the amount of solar energy available will determine the water delivery rate.

Due to switching the three-phase VSI that supplies the BLDC motor at its fundamental frequency, the switching loss of the VSI is greatly reduced.

II.DEVELOPMENT OF HCC BASED BLDC MOTOR

It is common practise for grid-connected inverters to use hysteresis current control due to its ease of implementation. In order for this control system to function, it compares the current at the single-phase inverter's output to a known reference current. To limit the error of the current as the controller generates switching pulses for the IGBTs, a fixed hysteresis bandwidth is used. This bandwidth is comprised of an upper limit and a lower limit. Hysteresis current control waveform and controller block diagram [17].

The phase current sensors are unnecessary for the BLDC motor drive that has been proposed. The BLDC motor-pump should be run at its rated speed regardless of the weather. To do this, the VSI's DC bus voltage must be maintained at the BLDC motor's rated DC voltage in a constant and reliable fashion. By controlling the DC bus voltage and, in turn, the operating speed, a bidirectional power flow control ensures that the full amount of power necessary to operate the water pumps is delivered. If there is no access to the grid or if the DC bus voltage is not kept at the rated DC voltage of the BLDC motor due to adverse environmental conditions, the motor's speed will be controlled by the DC bus voltage.

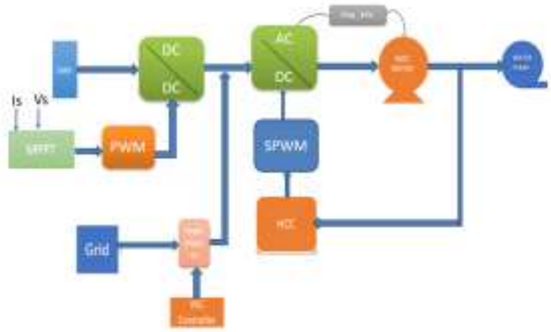

Figure.1: Block Diagram of grid interactive PV array-based water pumping system using a BLDC motor drive

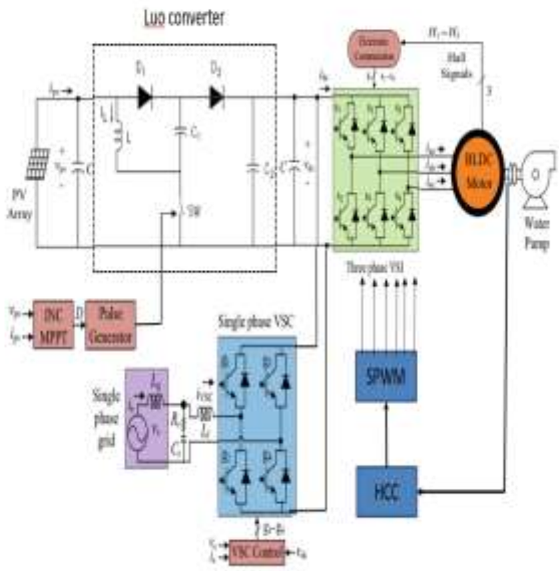

Figure 2: Power circuit of grid interactive PV array-based water pumping system using a BLDC motor drive

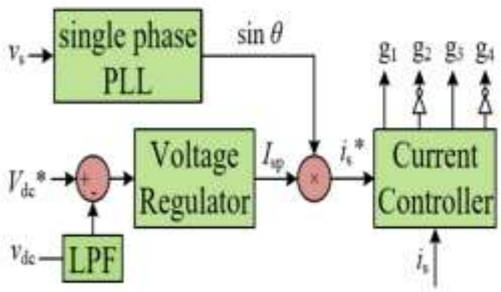

Figure 3: UVT based bi-directional power flow control of VSC

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III.BI-DIRECTIONAL POWER FLOW CONTROL

Grid-interactive PV generation allows for the construction of a trustworthy water pumping system and the optimal use of available resources. As can be seen in Fig. 2, a bi-directional power control is implemented using a UVT generation [18-19] to enable power flow in both directions. Since no elaborate mathematical model or algorithm is required, this method is the least complicated and most straightforward to put into practise. Voltage and current on the utility grid are synchronised using a Phase Locked Loop (PLL) with a single phase. At its fundamental frequency, it produces a supply voltage that is a sinusoid, denoted by sin. In contrast, the DC bus voltage, vdc, is controlled to extract the fundamental component of the supply current, Isp, in terms of amplitude. The voltage is controlled by a proportional-integral (PI) controller. A first-order low pass filter is used to filter out the ripple content of the detected vdc. After being filtered, vdc is compared to a predetermined threshold. Isp times sin yields is*, a crucial part of supply current. Gating pulses for VSC are generated by passing the sensed supply current, isis, through a current controller and then comparing it to the nominal current, is*, plus the error.

The voltage regulator produces a positive Isp when utility power is being drawn. As a result, a supply current is taken from the grid that is in-phase. Additionally, when PV arrays are used to supply the utility, an out-of-phase supply current is produced due to the negative Isp. In this way, power flow can be directed in whichever direction is most convenient by switching the current's direction. Total harmonic distortion (THD) and power factor are two measures of electrical power quality that the applied control method improves on the utility grid. If the power grid goes down, it will be impossible to control the DC bus voltage. Despite the PV array's sensitivity to weather, it can provide power to the water pump in autonomous mode. The Appendices provide a more in-depth look at the analysis of the proposed bidirectional power flow control.

IV.SYSTEM DESIGN

Getting the best performance possible from the setup depicted in Fig. 1 requires careful consideration of the many moving parts involved in its operation, including the PV array, Luo converter, single-phase grid, single-phase VSC, three-phase VSI, and brushless direct-current (BLDC) motor.

Here, we'll go over the thought processes that went into the design of these individual parts.

A. Design of PV Array

With a 1.3 kW BLDC motor-pump, a 1.5 kWp-PV array is ideal. It is calculated with the converter and motor-pump power losses included. Standard test conditions (1000 W/m2, 25°C, AM 1.5) are used to estimate the parameters. To achieve the necessary power output, we select a PV module-BMU/214 with an MPP voltage of 28.5 V and an MPP current of 7.5 A (full specifications are provided in the Appendices) [20]. The DC bus voltage of the VSI is taken into account when choosing the voltage of the PV array at MPP for the BLDC motor. We set it to Vmpp = vpv = 200 V, and then we can figure out the rest of the parameters as follows: This is the current at the power peak,

$$I_{\mathrm{mpp}} = i_{\mathrm{pv}} = \frac{p_{pv}}{v_{pv}} = 1500/200 = 7.5\ \mathrm{A} \quad (1)$$

where ppv = Pmpp = 1500 W is the power of PV array at MPP.

Series modules are as,

$$N_s = \frac{V_{mpp}}{V_m} = 200/28.5 = 7 \quad (2)$$

Parallel modules are as,

$$N_p = \frac{I_{mpp}}{I_m} = 7.5/7.5 = 1 \quad (3)$$

where Vm and Im are the module's maximum power point voltage and maximum power point current, respectively. To create a PV

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array of the necessary size, we connect seven modules in series, as shown in (2) and (3).

B. Design of Luo Converter

Estimating the input inductor L is a crucial part of designing a boost converter. It is chosen in such a way that the converter can be run in CCM under any atmospheric conditions. The estimated value of the duty ratio D1 is [21],

$$D_1 = \frac{V_{dc} - v_{pv}}{V_{dc}} = \frac{270-200}{270} = 0.25 \qquad (4)$$

where Vdc = 270 V is the DC bus voltage of the VSI. The inductor,

L is estimated as,

$$L = \frac{D_1 v_{pv}}{f_{sw}\Delta I_L} = \frac{0.25\times 200}{10000\times(7.5\times 0.2)} = 3.3\ \text{mH} \qquad (5)$$

where fsw is the switching frequency of boost converter; ΔIL is ripple in the current through L,

IL (= Impp).

C. Design of Three Phase VSI

The BLDC motor is supplied with power via a three-phase VSI. In order to create it, we have to make some educated guesses about the voltage, current, and VA ratings. To determine the necessary voltage rating of an IGBT switch, we use the DC bus voltage of 270 V as follows:

$$V_{VSI} = V_{dc}\times 1.4 = 270\times 1.4 = 378 \approx 400\ \text{V} \quad (6)$$

To account for the switching transients, a voltage safety factor of 1.4 is chosen. The current rating of an IGBT switch is determined in a similar fashion, where 1.3 is a current safety factor.

Finally, VSI's minimum VA rating is calculated as,

$$VA_{VSI} = V_{VSI} \times I_{VSI} = 400\times 7.5 = 3\ \text{kVA3} \quad (7)$$

D. Design of Single Phase VSC

To regulate power in both directions, a single-phase VSC is employed. In a single-phase VSC, the blocking voltage of switching devices is equal to the DC link voltage. The switches must be able to shut off 270 V of DC link voltage. A safety factor of 1.4 is selected to accommodate the voltage transients due to a high frequency switching. Therefore, the IGBT devices' estimated voltage ratings are

VVSC = Vdc×1.4 = 270×1.4 = 378

VVSC ≈ 400 V (8)

The VSC has a maximum current drawn from the grid or to be fed to the grid. The said current is estimated

$$I_{s,\max} = \sqrt{2}\frac{P_{mpp}}{V_s} = \sqrt{2}\frac{1500}{180} = 11.78\ \text{A} \qquad (9)$$

where the rms value of the voltage from the power company's grid is 180 V. Thus, the maximum current rating of IGBT devices is 11.78 A. The current estimated rating is, assuming a safety factor of 1.3

IVSC = Is, max × 1.3 = 11.78 × 1.3 = 15.3 ≈ 15 A (10)

Finally, the required VA rating of VSC is estimated as, VAVSC = VVSC × IVSC = 400×15 = 6 kVA (11)

E. Design of Common DC Link Capacitor

The boost converter, the three-phase VSI, and the single-phase VSC all share a DC link capacitor, C. The second harmonic component of the single-phase grid voltage appears on the DC bus of a single-phase VSC, and this is what the filter is tuned for. Accordingly, a rough calculation for capacitor C can be made:

$$C = \frac{I_{dc}}{2\omega_L \Delta V_{dc}} = \frac{1500/270}{2\times(2\pi\times 50)\times(270\times 0.008)} = 4700\ \mu\text{F} \qquad (12)$$

Where Idc is the typical DC bus current, L is the line frequency in radians per second, and Vdc is the DC bus voltage ripple.

F. Design of Interfacing Inductor

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The selection of an interfacing inductor, Lf depends on the permitted current ripple ΔIVSC. It is estimated as,

$$L_f = \frac{mV_{dc}}{4af_{SW}\Delta I_{VSC}} = \frac{1\times 270}{4\times 1.2\times 10000\times (1500/180)\times 0.2} = 3.3\ \text{mH} \quad (13)$$

where modulation index, m =1, over loading factor, a =1.2, switching frequency, fSW = 10 kHz, current ripple, ΔIVSC = 20% of IVSC.

VI. Simulation results and Discussion

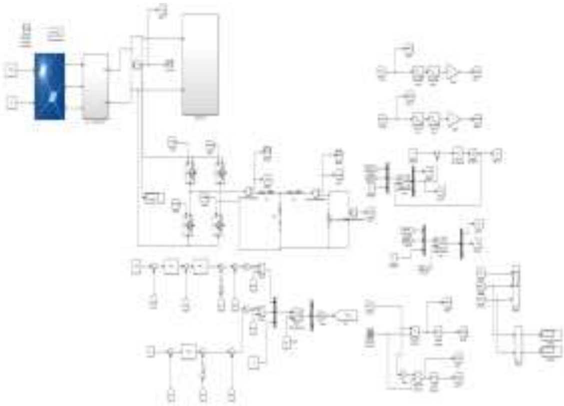

Figure 4: Simulation Diagram of Solar array fed with Luo converter and Hysterisis control Three Phase Inverter of BLDC motor driven water pump.

The system uses a Luo converter to improve DC link voltage regulation, reduces DC link voltage ripple, and also uses hysteresis current control technology, making it a PV array-based interactive water delivery system using BLDC motor drives. The operation of this control system works by comparing the measured output current of a single-phase inverter to a reference current. When the controller generates switching pulses for the IGBT, it uses a fixed hysteresis bandwidth consisting of upper and lower limits to control the current error within that range and improve torque, speed performance.

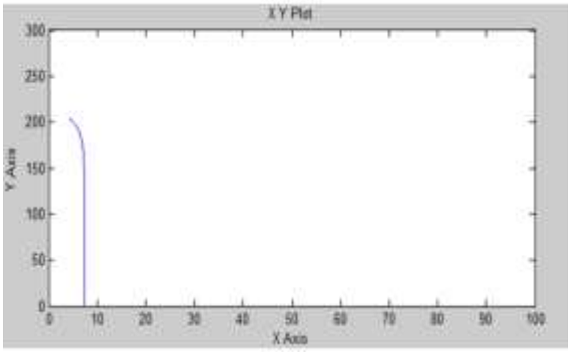

Figure 5: Solar IV characterises

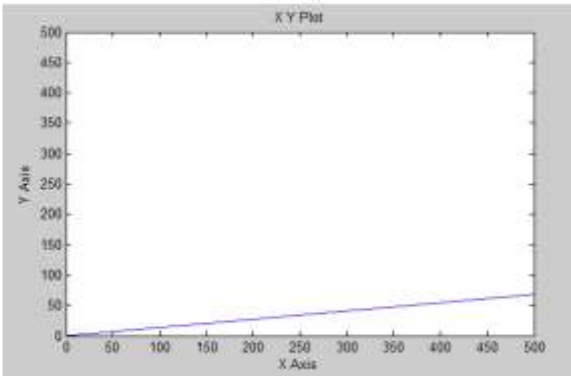

Figure 6: Solar PV characterises

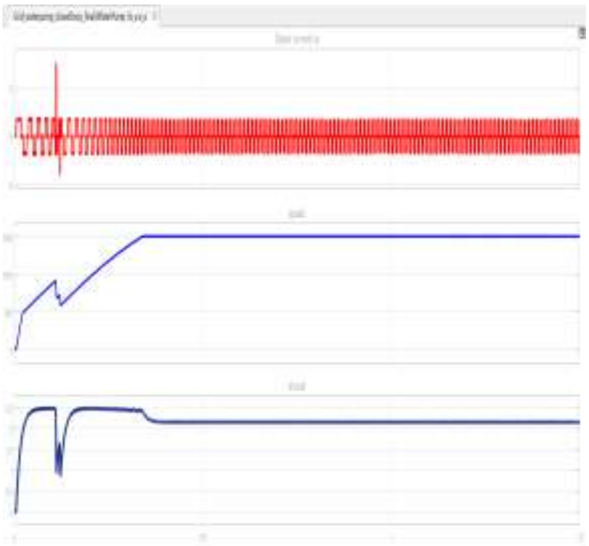

Figure 7: Stator current, speed & Torque of BLDC motor

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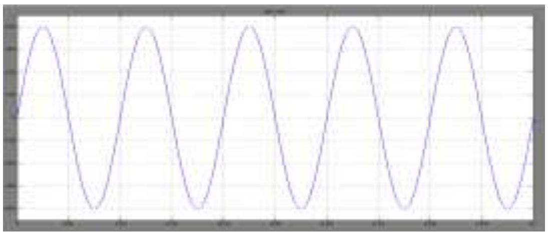

Figure 8: Grid input voltage

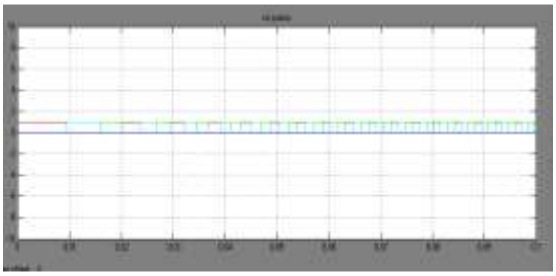

Figure 9: VSI switching signals

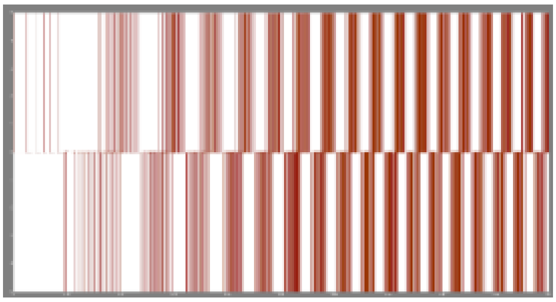

Figure 10: VSI output

Conclusion:

A single part grid interactive PV array based mostly water pumping system employing a BLDC motor drive has been projected and incontestable. A bidirectional power flow management of resource and water pumping with most capability in spite of the climate. The power flow has been adjusted in accordance with preferences using a simple UVT generation method.

The speed management of BLDC motor-pump has been achieved with HCC. With the change losses minimised thanks to the VSI's harmonic transformation, the system's overall power has been bolstered. Using the LUOconverter in this project, the conversion of power is high with less switching losses hightorque pulsation, less harmonic distortion, and has emerged as a reliable water pumping system once water pumping is required.

APPENDIX A

BLDC Motor Modelling:

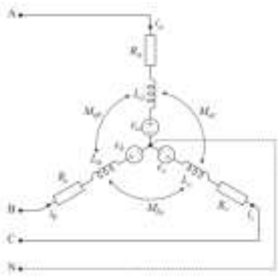

Figure 11: Equivalent circuit of three-phase BLDC motor

Dynamic model of BLDC motor Using the equivalent circuit, the set of voltage equations can be expressed as follows

$$u_a = u_{AN} = R_a i_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ca}\frac{di_c}{dt} + e_a$$

$$u_b = u_{BN} = R_b i_b + L_b \frac{di_b}{dt} + M_{ab}\frac{di_a}{dt} + M_{bc}\frac{di_c}{dt} + e_b$$

$$u_c = u_{CN} = R_c i_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{bc}\frac{di_b}{dt} + e_c$$

(14)

using the phase voltages (ua, ub, uc), The phase currents are denoted by symbols ia, ib, and ic, while the corresponding EMF symbols are ea, eb, and ec. Each phase's resistance is denoted by Ra, Rb, and Rc, while inductance is denoted by La, Lb, and Lc. as well as Mab, Mbc, and Mca, which stand for the mutual inductance between the two phases. Assuming the three phases of the motor are identical, we can rewrite (14) as (15) and have a simpler expression:

i.e., $R_a = R_b = R_c = R$, $L_a = L_b = L_c = L_s$, $M_{ab} = M_{bc} = M_{ca} = M$.

$$u_a = R_a i_a + L_s \frac{di_a}{dt} + M\frac{di_b}{dt} + M\frac{di_c}{dt} + e_a$$

$$u_b = R_b i_b + L_s \frac{di_b}{dt} + M\frac{di_a}{dt} + M\frac{di_c}{dt} + e_b$$

$$u_c = R_c i_c + L_s \frac{di_c}{dt} + M\frac{di_a}{dt} + M\frac{di_b}{dt} + e_c$$

(15)

According to Kirchhoff's first law, ia+ib+ic=0 and let the stator equivalent inductance be L=Ls-M, the following equations stand:

$$u_a = Ri_a + L\frac{di_a}{dt} + e_a$$
$$u_b = Ri_b + L\frac{di_b}{dt} + e_b$$
$$u_c = Ri_c + L\frac{di_c}{dt} + e_c \quad (16)$$

The electromechanical energy conversion is expressed as

$$P_e = e_a i_a + e_b i_b + e_c i_c = T_e \cdot \omega_m \quad (17)$$

where P is the electric power, T is the electromechanical torque produced by the motor (equal to the output torque on the shaft), and wm is the angular velocity of the mechanical part of the system in radians per second. If there is no mechanical rotating loss, Equation (17) indicates that all of the input electrical power is converted into the useful (mechanical) power. Afterward, the torque at the motor's output can be calculated.

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (18)$$

The dynamics of mechanical part is represented as follows:

$$T_e = J\frac{d\omega_m}{dt} + T_L \quad (19)$$

where TL is load torque, J is moment of inertia of rotor and coupled shaft. Using Laplace transform for (16) and (19), we have dynamic model of BLDCM in form of transfer function:

$$i_a = (u_a - e_a) \cdot \frac{1}{Ls + R} = (u_a - e_a) \cdot \frac{1/R}{\tau s + 1}$$
$$i_b = (u_b - e_b) \cdot \frac{1}{Ls + R} = (u_b - e_b) \cdot \frac{1/R}{\tau s + 1}$$
$$i_c = (u_c - e_c) \cdot \frac{1}{Ls + R} = (u_c - e_c) \cdot \frac{1/R}{\tau s + 1}$$
$$\omega_m = (T_e - T_L)\frac{1}{J \cdot s} \quad (20)$$

where s denotes the differential operator and $\tau = L/R$ is the electrical time constant of the motor. The complete dynamic model of BLDC is therefore expressed by (18) and (20).

Table.1: BLDC Motor Specifications

Parameter	Numerical Value
Stator Phase Resistance	2.87 ohm
Stator Phase Inductance	8.5e-3 H
Torque	2.2 N-m
Speed	1500 rpm
Stator Phase Current	2.5 Amp

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