J. Electrical Systems 20-6s (2024): 2768-2777

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Synergizing Battery-Powered Permanent Magnet Synchronous Motor Control with Integrated Modular Multilevel Converter Systems

Abstract: - This proposed work presents a comprehensive examination of a modular multilevel converter (MMC) combined with a permanent magnet synchronous motor (PMSM) for battery energy management in applications. In order to provide effective energy transfer and dynamic control, the Modular Multilevel Converter serves as a bridge between the battery system and the Permanent Magnet Synchronous Motor drive. By cleverly controlling energy flow and minimizing losses during charging and discharging cycles, the combination of MMC with PMSM seeks to increase energy efficiency and prolong battery life. Since the energy source provides all of the power for the motor, it runs at a constant pace. When the accelerating mode finishes, the energy storage receives just enough power to maintain a steady voltage. The energy storage system utilizes the majority of the renewable power generated by the electric motor when it is in deceleration mode to raise the voltage in the system. During the subsequent acceleration mode, the stored energy might be released the MMC-BESS, which combines a modular multilevel converter with a battery energy storage system, is gaining popularity due to its high adaptability and dependability. This system integrates batteries into a sub module. Sub-modular capacitor voltage fluctuations are caused by the significant reactive power that is generated through the workings of modular multilevel converters. To reduce the fluctuation, large capacitance capacitors is required, which would significantly increase the system's capacity. The proposed approach means to upgrade energy proficiency and execution in electric vehicle applications. By joining the benefits of battery power with the flexibility of MMC frameworks, the arrangement offers upgraded control accuracy, decreased misfortunes, and further developed adaptation to non-critical failure. This combination works with consistent power the executives, guaranteeing ideal use of assets while meeting severe execution prerequisites. Through exhaustive examination and recreation, the adequacy of this incorporated framework is illustrated, displaying propelling the field of electric vehicle impetus and power conversion potential.

Keywords: Modular Multilevel Converter, Permanent Magnet Synchronous Motor, Battery Energy Management, Battery Energy Storage System, Energy Transfer.

I. INTRODUCTION

Power electronics converters used in high-voltage as well as high-power applications face additional problems brought about by the growing popularity of grid-connected uses of large-scale energy from renewable sources in recent years. By reducing the voltage rate need of switching devices, multilevel topologies are able to achieve larger voltage levels. Extensive research over the last decade has focused on a modular multilevel converter as the most promising of the current multilevel topologies [1][2]. Among the many benefits of multilevel converters are their modular designs, which allow for less voltage stress on switching devices and an output voltage with a low harmonic content [3]. The MMC topology uses half as much power as the cascaded H-bridge design due to its modular construction, yet it only uses half the arm current [4]. The figure 1 shows the interconnecting DC

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micro-grids using MMC. Motor drive systems benefit from in-energy storage devices for improved dynamic performance as well as effectiveness since these devices can recover regenerated energy and provide peak power during transients. With the use of power-electronic technology, motor drive systems may achieve effective power control among energy sources as well as energy storage[5][6]. Typical motor driving systems use bidirectional dc-dc converters to link the power supply to the stored energy. By arranging the system in this way, it is possible to develop a power management approach that is flexible with respect to the source of energy, the energy storage, as well as the motor, and to reduce the detrimental impact of energy storage voltage variation upon system performance.

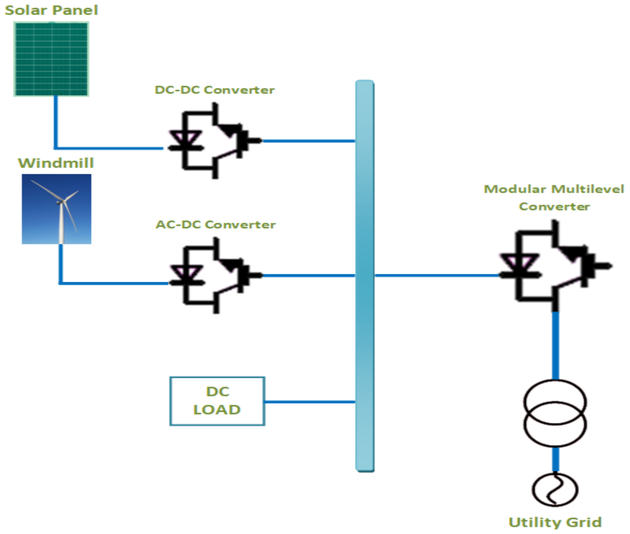

Figure.1:Interconnecting DC Micro-Grids using MMC

Nevertheless, a dc-dc as well as a dc-ac stage is required for energy conversion and all the way from the generator to the battery to the motor[7]. The figure 2 shows the control schematic for DC-link voltage.

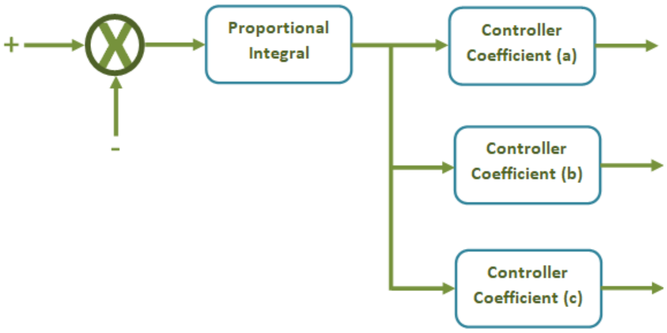

Figure.2:Control Schematic for DC-Link Voltage

Furthermore, the efficiency of the dc-dc converter is reduced due to the high switching and conduction losses that occur in a high-power application[8]. It also makes the system more complicated and expensive, and it causes stability issues, particularly in situations with significant inrush currents. One possible alternative to these dc-dc converters is the usage of Z-source networking. However, even with a large boosting proportion, low input voltage, and a significant output voltage, the loss inside the unique Z-source network is still not completely insignificant.

Many high-power uses, including hybrid energy source systems, motor drives, as well as static synchronous compensation, use cascaded multi-layer inverters[9]. Applications needing substantial power, including heavy-duty electric as well as hybrid vehicles can reap the benefits of motor drive systems that interface with cascaded multi-layer inverters. Modularity helps keep prices down for a number of reasons, including its support for inexpensive semiconductor applications and low production costs. A transformer-less architecture, reduced electromagnetic interference, enhanced fault tolerance, and great power characteristics at lower frequencies are just a few of the many attributes of the cascaded multilevel inverter. This design's excellent energy efficiency is also due, in part, to the single-stage energy conversion that occurs among the energy sources and the motor. To further facilitate scaling to high voltage as well as high power, it can also facilitate the interface of energy storage or a segmented source of energy to the modular structure. There have been recent accounts of cascaded multi-layer inverters that use a single power supply and several capacitors to store energy for use in motor drives. Nonetheless, the main purpose of capacitors in this investigation was to provide harmonic cancellation. The energy storage's capabilities were limited since the real power distribution was not uniform between the source and the store [10].

II. RELATED STUDY

Motor drive systems may now attain great levels of integration, control bandwidth, efficiency, and power density thanks to the advent of fast-switching wide-band-gap powered electronic components [11]. There is a noticeable rise in motor over-voltage at the motor terminals as well as stator neutral due to the fast-switching speed as well as the high switching frequency. Because of the increased voltage, the insulation and bearings of the motor windings are under more stress. Motor terminal over-voltages in differential mode (DM) (phase-to-phase), common mode (CM) (phase-to-ground), and CM stator neutral (motor neutral to ground) are all examined in this study [11].

This study delves into the impacts of higher switching speeds and switching frequencies on motor over-voltage, as the previous research has mostly ignored the elevated switching frequency impact [11]. A considerable over-voltage occurs when the periodicity of the switch or its multiples coincides with an anti-resonant frequency of the cable or motor. Using the anti-resonant behavior in the cable as well as motor impedance, we have found the over-voltage oscillation rates and discussed the over-voltage observations for the three types of motor over-voltages. We have tried the analysis both with and without four-core cables using a 7.5kW motor arrangement, and a three-phase inverter controlled by SiC or GaN. The inverter can handle switching frequencies up to 250 kHz and switching speeds up to 40kV/μs. Further testing revealed that the motor bearing current—a0 leading factor in bearing deterioration-increases as a result of the high frequency impact [11].

Power conversion systems operating at medium to high voltages can benefit from a modular multilevel converter topology [12]. Among the many appealing aspects of the MMC are its modular design, scalability in voltage and current, transformer-less functioning, fault blocking capabilities, small filter size, low output current ripple, high efficiency, and cheap redundancy expense. Because of these advantages, MMC topologies, their functioning, and control have been the subject of much research in recent years. The mathematical models and MMC topologies are reviewed in this paper. We also go over the modulation methods and control systems (classical and model predictive controls) that they use. Lastly, we emphasize the potential problems of MMC applications [12].

There has been a lot of buzz about the newly created modular-multilevel converter (MMC) in both academia and business, and it's quickly becoming a practical technology for a wide range of medium- and high-power uses [13]. Current power conversion technology has enhanced MMCs in various ways, such as making them more efficient, making them more modular, improving power quality, allowing them to operate without transformers, making them more cost-effective, making better use of standard components, increasing availability, and producing wave-forms with excellent quality. On the other hand, MMC topologies have a number of advantages, such as smaller size, less semiconductor losses, and less voltage stress. Because of these features, high-power applications, including distribution and HVDC transmission systems, have a reduced operating cost. Examining MMC applications and various circuit topologies is the primary contribution of this paper. Converter architectures containing sub-module converters and members of the MMC family make up these MMC combinations. This generalizes MMC applications, which in turn reduces size and cost by half, boosts system reliability by decreasing conduction and switching losses, and so on. We have also looked at the benefits and downsides of each MMC application. With regard to the aforementioned study fields and novel applications, this review shows the most recent performance of MMC [13].

Due to its many benefits over the conventional voltage source converter, the modular multilevel converter architecture has recently emerged as the preferred choice for power conversion applications involving medium to high voltages [14]. However, ensuring system reliability in real-world applications is rather challenging because of the high number of sub-modules (SMs) in the MMC. Every SM has the potential to be a point of failure. This research proposes a Markov model reliability evaluation for the MMC. The first step is to examine the frequency of power electronic device and SM failures. The next step is to construct the system's state transition equation and Markov model. The reliability assessment of the MMC with redundant SMs and the mean time to failure are likewise included in the defined general reliability evaluation function. The results confirm that the reliability assessment based on the Markov model might be a helpful guide for project design [14], and they conclude by analyzing a real example of a direct current distribution for reliability evaluation.

Secondary functions, including main frequency control and load management, are supplied by utility-scale ESS [15]. In order to take advantage of the topology's flexibility, dependability, and high efficiency, ESS integration into Modular Multilevel Converters is being suggested as of late. Power may be transferred between the ES branches and the ac or dc sides of a modified MMC topology that is designed and controlled in this study. The topology includes partially-rated Energy Storage Cascaded H-Bridge branching that is integrated with some MMC stacks in parallel. In order to accomplish energy balancing among the divided sub-stacks, the controller as well as balancing algorithms is described in detail, along with the system's state-space dynamics. We provide power flow scenarios with a 0.05pu ES contribution and show that there is a power step shift. Also covered are the stacks' energy deviations and their overall effects on converter ratings, with an emphasis on the improvements required to boost power capability [15].

III. METHODOLOGY

This research details the design, modeling, and management of a hybrid system that uses fuel cells and batteries to power the Metro Centro tramway in Seville, Spain. To supplement the output of the tramway's polymer electrolyte membrane FC during acceleration (or other times when needed), cruising, as well as energy recovery during braking, the suggested hybrid system incorporates a nickel-metallic hydride cell battery. In order to move the trams, four traction inductive motor drives are employed. The ancillary services are likewise powered by the hybrid system. A FC-side boost-type unidirectional dc/dc converter as well as a battery-side boost-type bi-directional dc/dc conversion makes up the power conditioning system. The figure 3 illustrates the current system's block diagram.

Using a combination of renewable energy sources and distributed energy storage, this research proposes a motor driving system. It relies on multi-layer inverters that cascade. Notably, by recovering regenerating power from the motor as well as improving the system's dynamic operation and electrical quality, an autonomous power regenerating controller can achieve an effective real-power distribution between the electric motor, battery storage, as well as the energy source, thereby reducing the adverse effects of power fluctuations on the sources.

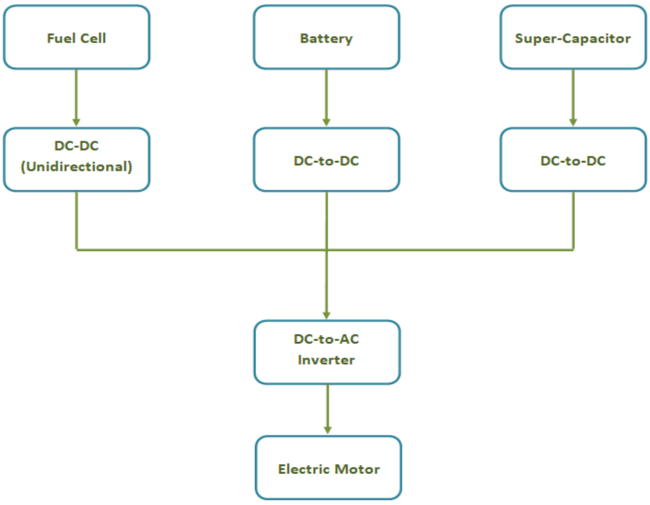

Figure.3: Block Diagram for Existing Model

The recommended setup uses cascaded multi-layer inverters to supply power to the motor using segmented energy storage. The main inverter is connected to the power supply, while the auxiliary inverter is connected to the energy storage. Both inverters are three-level H-bridges. One main inverter and n auxiliary inverters make up each step of the stacked multi-layer inverters cell. To find out how many auxiliary-inverter cells are needed for each phase, you may look at the cost-benefit analysis of power loss, power quality, as well as power compensation capabilities. Better power quality as well as enough power adjustment, for example, might be achieved with a higher cell density. However, this leads to a more complex control strategy, more devices, and more expenses. The MMC-BESS, which combines a modular multilevel converter with a battery energy storage system, is gaining popularity due to its high adaptability and dependability. This system integrates batteries into a sub module. Sub-modular capacitor voltage fluctuations are caused by the significant reactive power that is generated through the workings of modular multilevel converters. To reduce the fluctuation, large capacitance capacitors is required, which would significantly increase the system's capacity. The figure 4 shows the suggested system's block diagram.

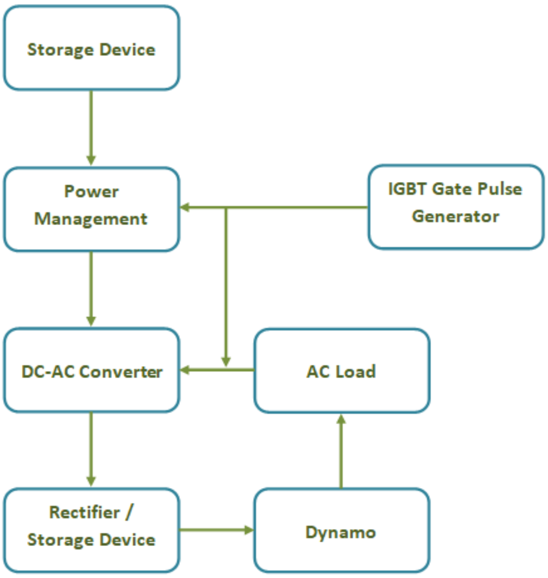

Figure.4: Block Diagram for Proposed Model

The proposed technique can improve the efficiency, responsiveness, as well as power quality of the electric ship of the future by enhancing the drives of high-power motors. Segmented ultra-capacitors also allow for isolated energy storage, which is useful for large electric vehicles with powerful motors. In such situations, separate battery packs might serve as the energy supply. The system's segmented storage of energy allows for a significant reduction in battery size and the use of a lower voltage battery, which in turn reduces the overall price of the battery. A further benefit of the cascaded design is the ability to use a UC with a lower voltage. Due to these reasons, the UC active interface is considerably more powerful and outlasts the battery in terms of cycle life. Both the battery as well as the UC stands to gain from a cascaded design in terms of increased fuel economy, a shorter system dynamic, an extended life cycle, and less battery loss. During this time, the discharging process will cause the voltage of the energy storage to drop. When the electric motor is operating at a constant speed, all of the power comes from the energy source. Just enough power is sent to the energy storage to keep the voltage constant when the accelerating mode ends. When the electric motor is in deceleration mode, the system for storing energy collects most of the renewable power and uses it to increase the system voltage. It is possible to discharge the accumulated energy during the next acceleration mode. The figure 5 illustrates the circuit diagram of PMSM drive system architecture based on MMC. The MMC is a power electronics converter that achieves high voltage conversion with less harmonic distortion and more efficiency by arranging several power semiconductor devices in modular cells. Its fault tolerance and scalability are enabled by its modular structure. The MMC is in charge of turning the battery energy storage system's DC electricity into AC power that can run the PMSM. An electric motor with permanent magnets incorporated into its rotor is known as a PMSM electric motor. It is renowned for having excellent torque density, great efficiency, and accurate speed control. Within the PMSM drive system based on MMC, the PMSM serves as the primary electro mechanical component that transforms electrical energy into mechanical motion for vehicle propulsion.

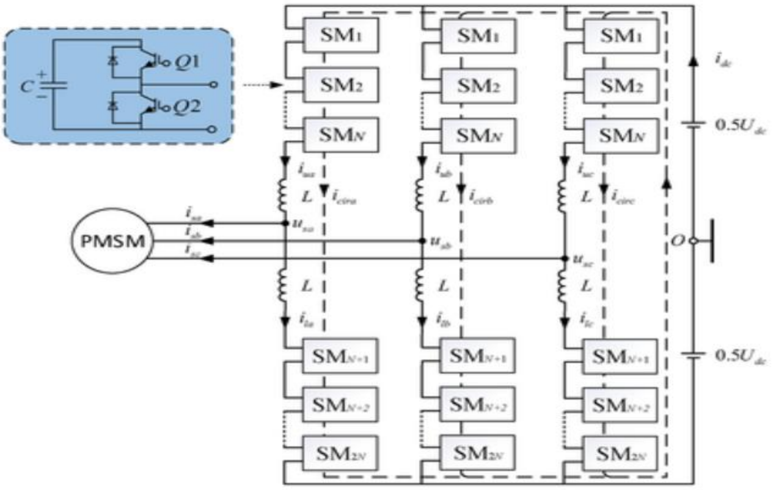

Figure.5: Circuit Diagram of PMSM drive system architecture based on MMC

The BESS supplies the MMC with the DC power input, and the MMC transforms it into AC power for the PMSM. Depending on the demands of the particular application, the BESS may consist of several battery types, such as nickel-metal hybrid batteries, lithium-ion batteries, or other energy storage technologies. When it comes to controlling how the MMC and PMSM operate, the control system is essential. Power flow management, voltage and current maintenance, torque and speed control techniques, and overall drive system coordination are all accomplished by means of algorithms and software. Protection measures and monitoring sensors are also incorporated into the MMC-based PMSM drive system to guarantee dependable and safe operation. This could include capabilities for defect detection, over-current and over-voltage protection, and diagnostics to find and fix possible problems.

A. Results and Discussions

The MMC-BESS's suggested control approach, a scaled-down prototype was constructed in the lab; Fig-6 shows the layout of the simulation. In each stage of the design process, the prototype's controller structure relies on a single Digital Signal Processor (DSP). To keep costs down, the battery module is divided into individual sub modules and uses three 12 Volts 24 Ampere lead acid battery cells. Keep in mind that DC-to-DC converters that use MMCs have a different switching frequency than those that use batteries. Because individual batteries often have a lower power rate than the MMC side, the DC-to-DC converter on the battery side allows for independent selection of semiconductor components and switching frequency. Improved high-power conversion efficiencies between batteries and MMC are possible thanks to wide band gap devices. For the sake of experimental confirmation, a compact 5.5 kW PMSM system of drives was constructed. The principal characteristics of the PMSM. The primary inverters receive their power from three independent rectified dc sources. With two transmitted auxiliary inverters per phase, the motor driving systems may simulate the functioning of a single UC element. These in turn interface with 20 mF electrolytic capacitors. An adjustable voltage range of 37.5 to 75 volts is used for the capacitor, with the dc source voltage set at 150 volts.

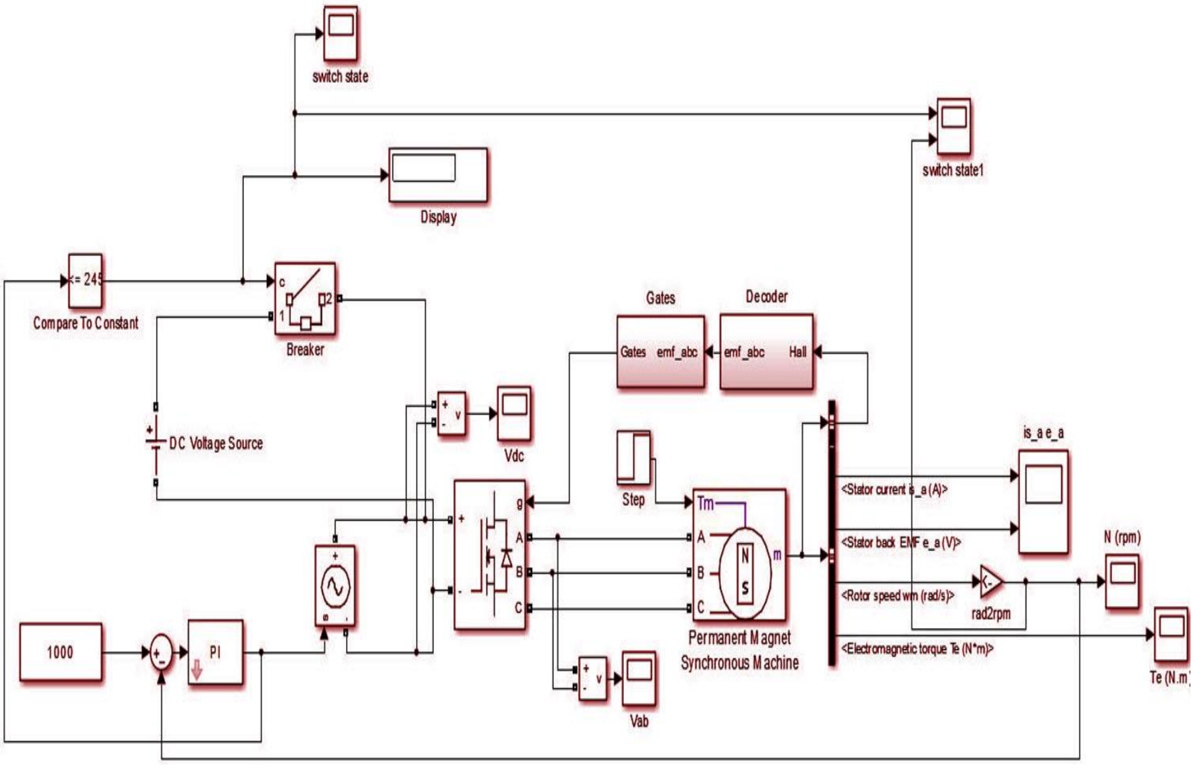

Figure.6: Simulation Diagram of PMSM with MMC

To begin, we tested the suggested motor drive system in a simulated environment using a MATLAB/Simulink hybrid platform along with PSIM. Findings from simulating a normal driving cycle with acceleration, deceleration, and constant-speed mode Experimenting with a fixed load torque of 10 N m and varying the speed command N between 0 to 2000 r/min during 0.1 s and back to 1000 r/min in 0.4 s demonstrates the speed dynamic reaction. Nearly follows N's movements exactly. The simulation diagram of PMSM with MMC six correlated capacitor voltages are shown in figure 6. At startup, acceleration mode makes use of a capacitor value of 75 V. The voltage drops from 75 to 51.5 V because the capacitors are exhausted to generate the peak power needed during acceleration. The capacitors require almost no direct current power to maintain 51.5 V once they are in motion. Capacitors draw regenerative energy from the PMSM, which causes their voltages to increase from 51.5 to 62.5 V. when the vehicle decelerates. All six capacitors are kept in a state of balanced symmetry by the capacitor voltage balancing control, which works during the whole driving cycle.For simulated wave forms of P Motor, P Storage, as well as P Source, respectively. The P Motor draws a maximum of 4200 W while in acceleration mode; capacitors provide up to 3000 W of this, and the rest comes from dc sources,To the PMSM gives stator current and Electromotive force as seen in Fig 7.

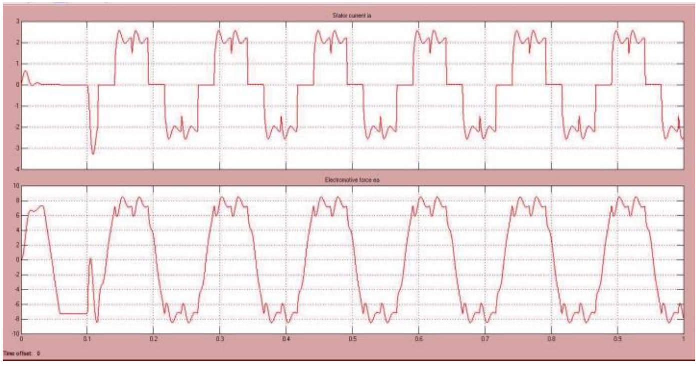

Figure.7: Waveform of Stator Current and Electromotive Forces

The capacitors start powering the PMSM at 0.12 s and keep going until the speed hits 2000 r/min. The relevant energy may be calculated using the following figure, Fig -8. A voltage may be obtained by using the capacitance range (3). Findings in Fig-9 show that a voltage adjustment of the capacitor from 75 to 51.5 V is sufficient to meet the power demand of the PMSM with MMC it generate constant speed and electromagnetic Torque shown in Fig 8-9 indicate that the capacitors can handle 3500 W, even if the PMSM only has a regenerative peak output of 1800 W. The capacitors soak up power from the PMSM's regeneration as well as power from the DC sources, because the power from the DC sources decreases linearly throughout the deceleration phase.

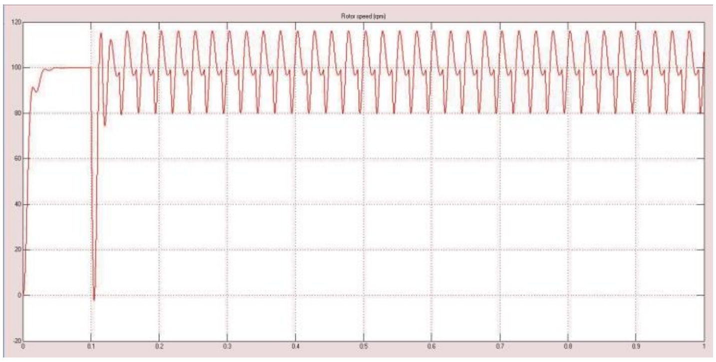

Figure.8: Waveform of Rotor Speed

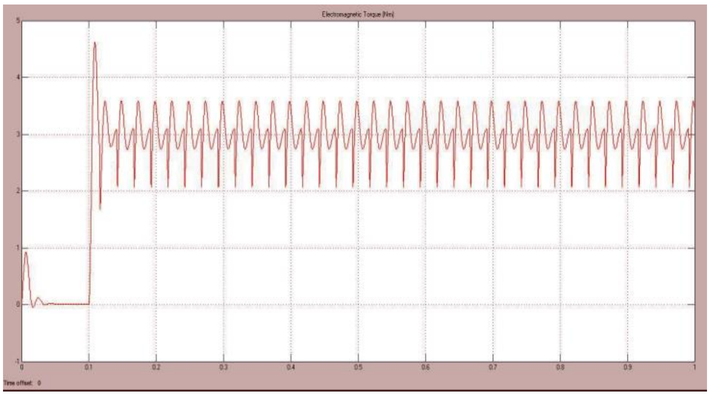

Figure.9: Waveform of Electromagnetic Torque

IV. CONCLUSION AND FUTURE SCOPE

The combination of a Permanent Magnet Synchronous Motor (PMSM) control drive and a Modular Multilevel Converter (MMC) in a battery energy storage system offers a cutting-edge and eco-friendly solution for a range of uses, this system can be used especially in renewable energy systems and electric vehicles (EVs). Voltage management, and smooth energy conversion from battery energy storage to PMSM drive are all made possible by the MMC's fault-tolerant, modular architecture and accurate control algorithms.By using integration of PMSM-MMC connections use to control the speed of the motor ,electromagnetic torque and Stator current. And again through this integration, energy consumption and carbon emissions are decreased, power quality is improved, and energy use is optimized. Overall, the MMC converter connected to a PMSM's control drive and equipped with a battery energy storage system is a state-of-the-art method for producing dependable and environmental. Through complete investigation and recreation, it is apparent that this incorporated methodology offers predominant control accuracy, decreased misfortunes, and further developed adaptation to internal failure. This examination highlights the capability of coordinated frameworks to propel electric vehicle drive and power change innovations toward a maintainable and effective future.

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