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CONTROL AND OPERATION OF AN IMPROVED MMC BASED DRIVE WITH ENHANCED POWER QUALITY FEATURES

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ABSTRACT

In this project renewable operated modular multilevel converter (MMC) has emerged as a suitable topology for high power drive applications. However, the voltage fluctuations of its floating capacitors increase the control complexity of the converter. In this project, the RES fed MMC dc-port voltage is manipulated to regulate the amplitude of these fluctuations to a constant value during the whole frequency range. The proposed approach has several advantages when compared with the conventional ones since it minimises the voltage fluctuation in the capacitor cells. Additionally, it decreases the common-mode voltage at low frequencies and the capacitor rms current, increasing their expected lifespan and reducing the winding insulation damages and the leakage currents in the bearing of the machine. The effectiveness of the proposed control strategy is validated with a laboratory-based prototype composed of 18 power cells, feeding a vector-controlled induction machine.

INTRODUCTION

Since the invention of the modular multilevel converter (MMC), this topology has been proposed for applications such as rail train [1], high-voltage dc transmission (HVDC) [2] and machine drives [3–16]. Although the MMC has several advantages over others high power modular converters (mainly for quadratic torque-speed profile loads [3, 4]), significant efforts are still required to improve its performance for drive applications. The MMC topology is shown in Fig. 1. The converter is composed of six 'clusters' connected to form an ac port that feeds the machine and a dc port. Each cluster has an inductor L and n cascaded half-bridge modules. The energy in each cell is stored by a 'flying' capacitor C.

Consequently, the proper operation of the MMC-based drive requires a control system to maintain the capacitor voltage balanced. This target is complex to achieve when the machine is operating at low speed because large voltage fluctuations occur in the capacitors. For this reason, in the so-called 'low-frequency mode' (LFM), mitigating variables (circulating currents and common-mode voltage) are used to reduce the voltage fluctuations, maintaining them within an acceptable margin [7, 8, 13, 17]. On the other hand, when the mitigating signals are no longer required, the 'high-frequency mode' (HFM) is enabled. As is well known, the lifetime of electrolytic capacitors is nominally below semiconductors lifetime.

Regarding reliability, this fact represents a significant drawback of MMC family because its capacitors are always subjected to voltage fluctuations. In consequence, several control strategies have been proposed to decrease the voltage capacitor oscillations. Another approach is developing new dielectric material capacitors, such as film capacitors, to extend the lifespan of cell capacitors, and there is an important ongoing research being carried out and new material capacitors, such as film capacitors, represent an excellent alternative to extending the lifetime of the cell capacitors [18, 19]. A novel control system for the MMC-based drive is proposed to solve the problems mentioned above. This new control scheme considers the manipulation of the dc-port voltage as a function of the capacitor voltage fluctuations.

The major advantage of this methodology is that the capacitor voltage fluctuations are regulated within a pre-defined margin during the whole frequency range. Accordingly, contrary to the conventional approaches, the amplitude of the capacitor fluctuations is not dependent on the

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machine frequency, and it can be minimised as much as possible, reducing the rms current in the capacitors and increasing their expected lifespan. What is more, this work shows that the common-mode voltage and circulating currents are reduced at the start-up of the machine when the dc-port voltage is regulated as proposed, eliminating problems such as winding insulation damages, leakage currents in the bearing etc.

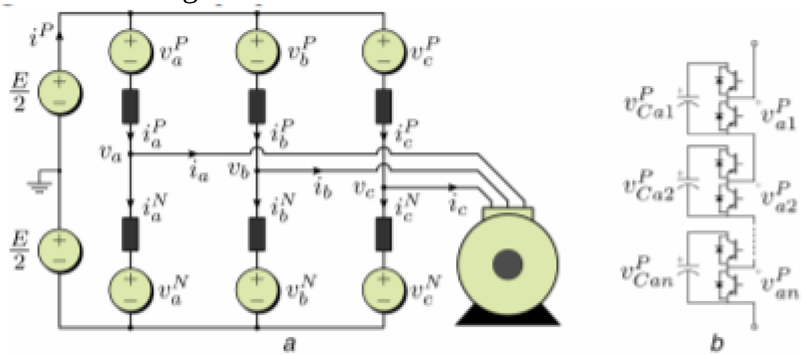

FIG 1 PROPOSED CIRCUIT BLOCK DIAGRAM

A resistor bank has been connected to the PMG output providing a 4 kW load at nominal speed. Hall-effect transducers are used to measure the dc-port voltage, the capacitor voltages and the cluster currents. To control the system, a platform based on two field-programmable gate array boards (Actel ProASIC3) and a digital signal processor (TI TMS320C6713) is used. A complete description of the control diagrams utilised in this work can be found in [12, 14, 20]. Fig. 4 depicts the dynamic performance when the MMC drives the induction machine from 0 to 2000 rpm for constant (left) and manipulated (right) dc-port voltage. The speed profile for both test is shown in Figs. 4a and b. Notice that this profile includes the machine start-up and the zero-crossing condition, what represents the worst case situation for an MMC-based drive. The machine currents are shown in Figs. 4c and d, demonstrating that the same mechanical load was applied during the tests. The dc-port voltage (blue line) and the desired output voltage of a cluster (red line) are depicted in Figs. 4e and f. As shown, the MMC cluster has to synthesise a high common-mode voltage during the LFM because the nominal dc-port voltage is applied during the machine operation. This is concluded based on the highfrequency signals of the output cluster voltage at low-frequencies [see (17)]. However, the required common-mode voltage is naturally lower when the dc-port voltage is reduced as in Fig. 4f. Notice that in these experimental results, the voltage E was regulated to a 50% of its nominal value in LFM, which represent a feasible reduction for the aforementioned input converters [21–24]. The total cluster voltages are shown in Figs. 4g and h. As discussed in Section 3, a margin-based control strategy maintains their amplitudes constant during LFM [20]. Notice that their peakto-peak value for a constant dc-port voltage is 40 V; however, it is possible to reduce this fluctuation to 20 V peak-to-peak applying a manipulated dc-port voltage, increasing the expected lifespan of the capacitor cells and decreasing their rms current [23]. What is more, this amplitude is maintained constant by manipulating E as the machine speed increases in HFM. Figs. 4i and j depict the obtained circulating currents during these tests. It is important to mention that the peak value of both currents is similar, and then the converter current rating has not to be increased when the proposed strategy is implemented, as demonstrated in Figs. 4k and l, where it is shown that the cluster currents have a similar peak-value for both tests.

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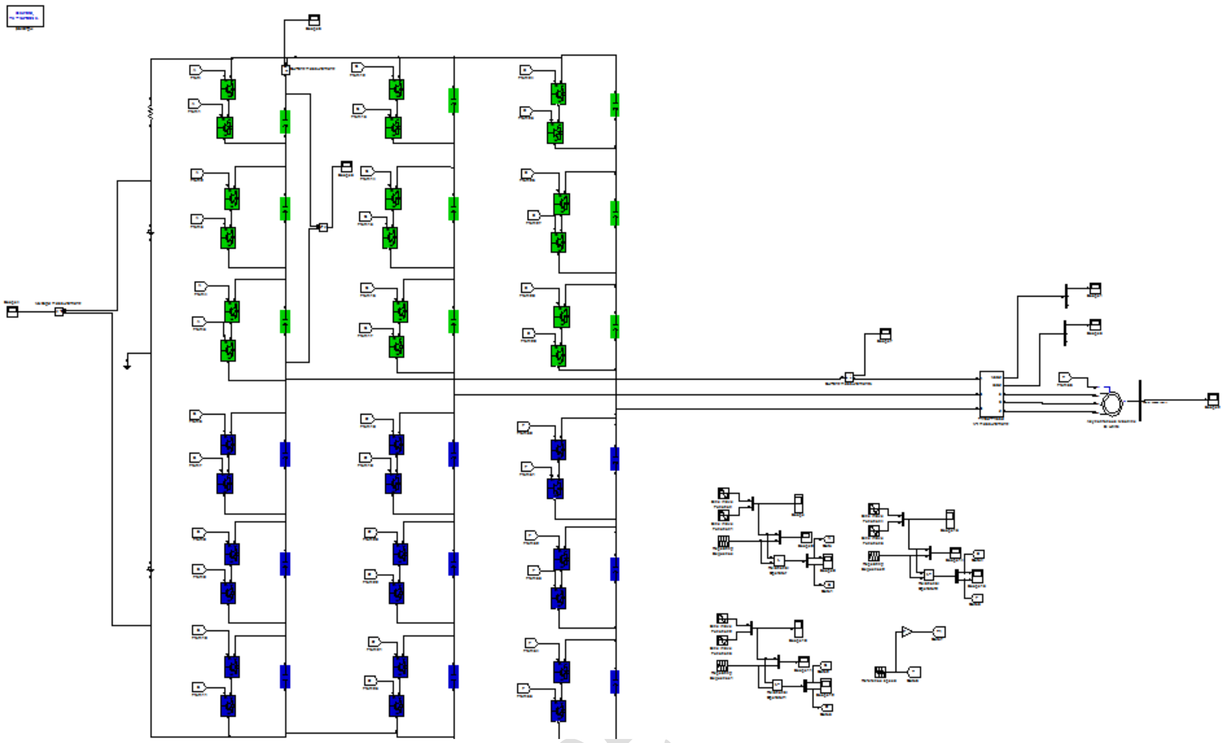
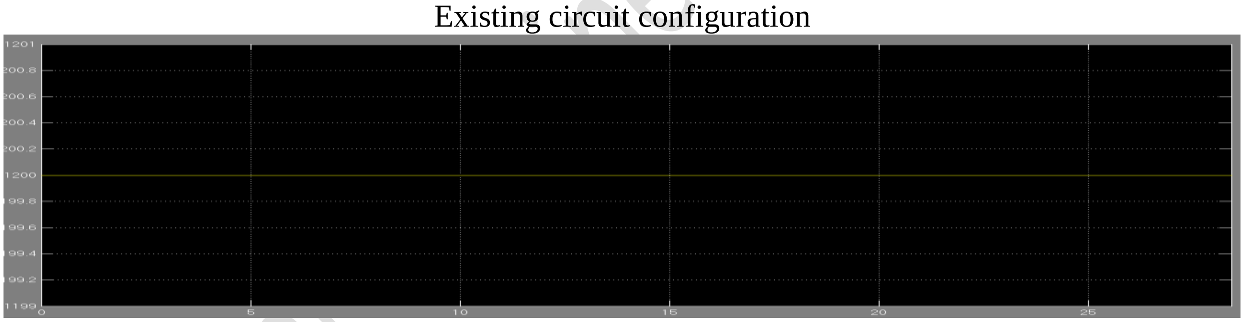
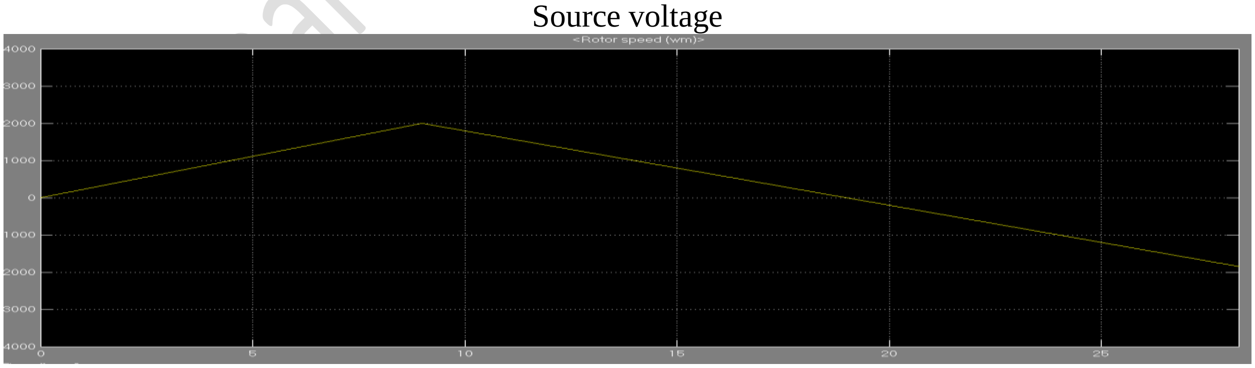
Existing and proposed system



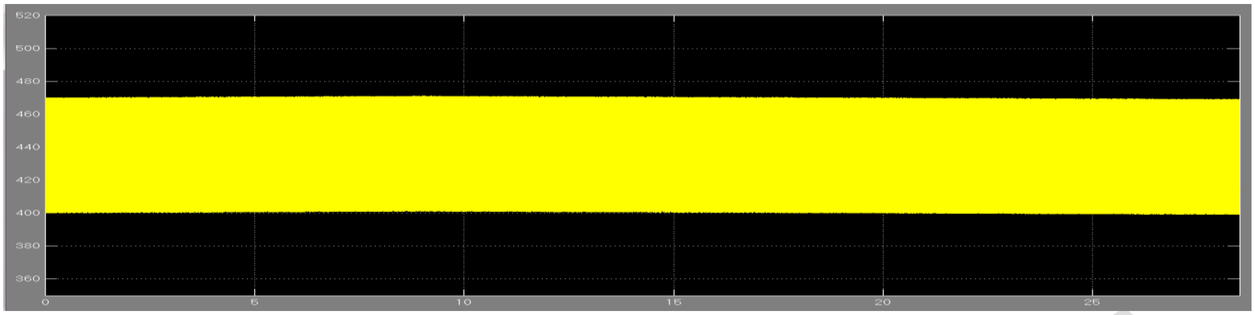
Existing circuit configuration



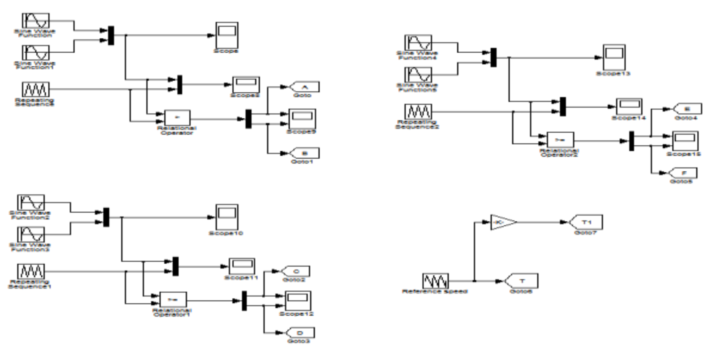
Source voltage



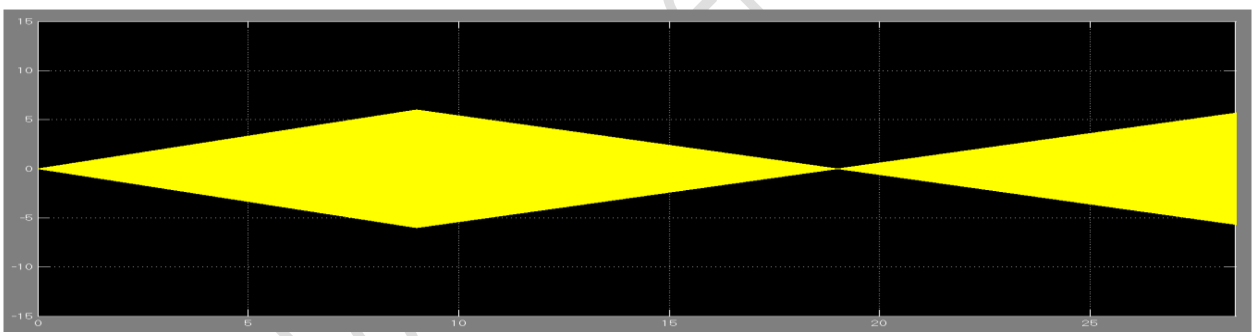
Reference speed vs time



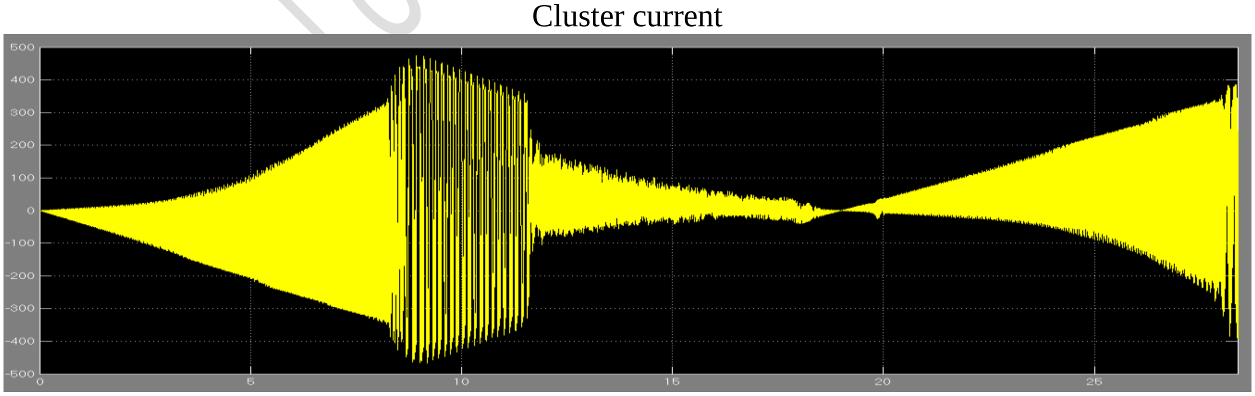
Cluster across voltage



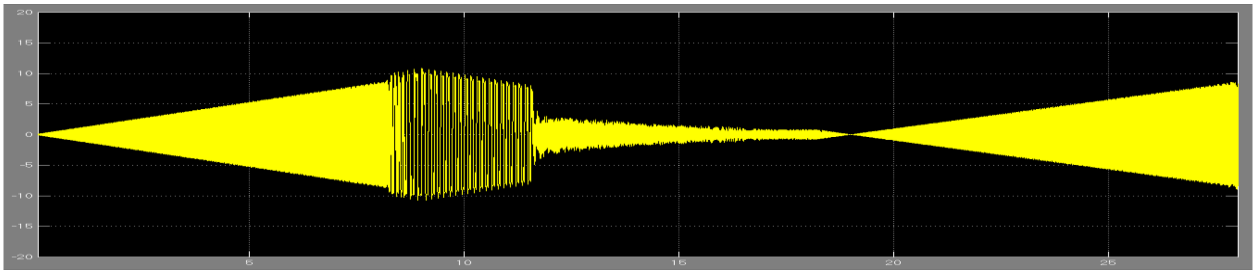
Proposed controller



Cluster current



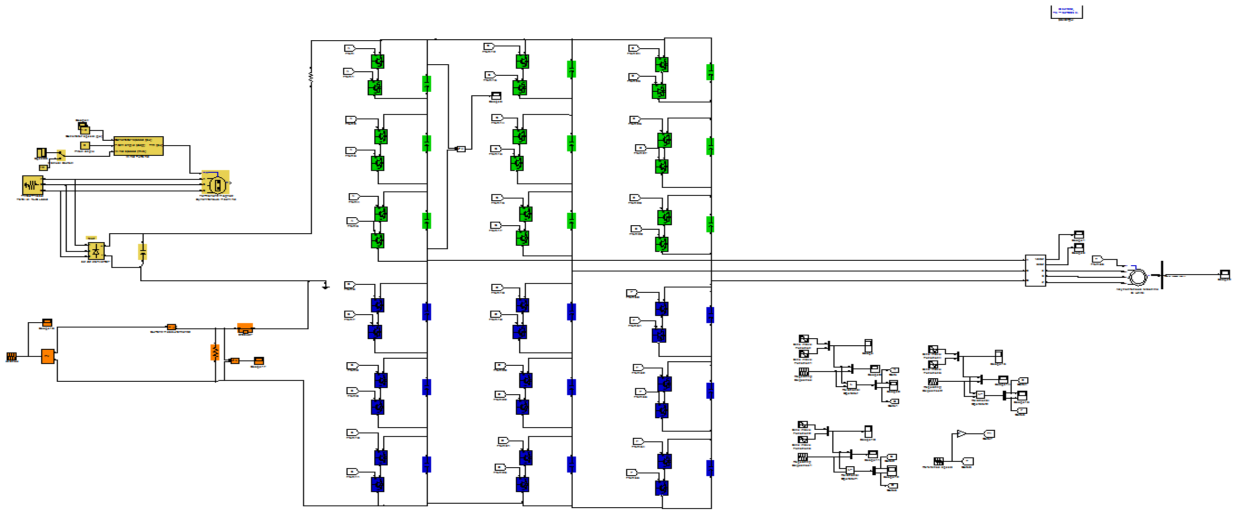
Voltage across the machine



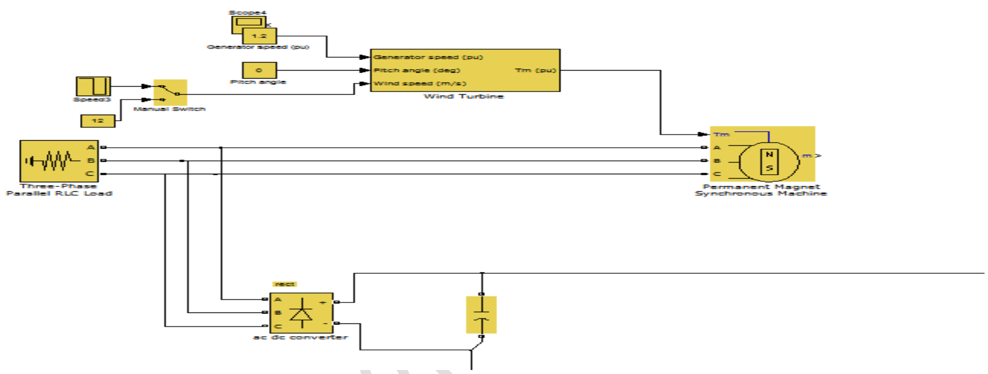
Machine current vs time

Wind-driven stand-alone systems have proved to be a reliable energy solution, capable of satisfying the electrification needs of numerous remote consumers around the globe, especially in cases where the local wind energy potential is medium to high. Even so, where local conditions are not as favorable, oversizing of the wind turbine and the excessive energy storage capacity required discourage consumers from proceeding with RES installations [48]. On the other hand, there are several areas on our planet where one may encounter both abundant availability of solar energy and high or medium-high wind energy potential, the combination of which may substantially reduce the energy storage requirements of the traditional wind-based stand-alone systems. Solar and wind energy availability vary greatly over time and therefore normally cannot match the time variation of the load demand if operating independently. In this context, both photovoltaic and wind energy stand-alone systems require oversized storage capacity in order to fulfill the energy demand of remote consumers. The complementary nature of wind and solar can smooth out the variation in the energy production of the system leading to a significant decrement of the energy storage requirements.

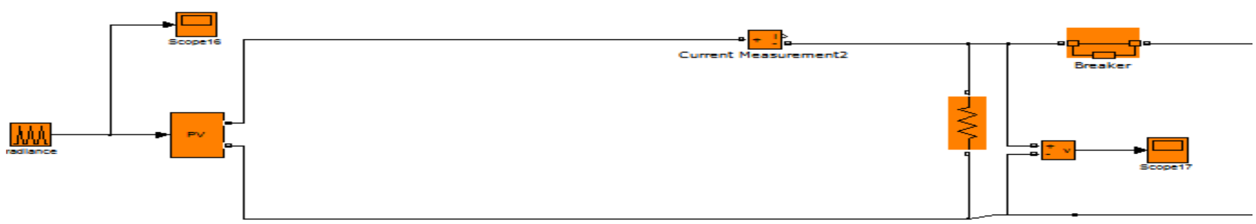
Many remote communities around the world cannot be physically or economically connected to an electric power grid. The electricity demand in these areas is conventionally supplied by small isolated diesel generators. The operating costs associated with these diesel generators may be unacceptably high due to discounted fossil fuel costs together with difficulties in fuel delivery and maintenance of generators. In such situations, renewable energy sources, such as solar photovoltaic (PV) and wind turbine generator provide a realistic alternative to supplement engine-driven generators for electricity generation in off-grid areas. It has been demonstrated that hybrid energy systems can significantly reduce the total life cycle cost of standalone power supplies in many off-grid situations, while at the same time providing a reliable supply of electricity using a combination of energy sources. Numerous hybrid systems have been installed across the world, and the expanding renewable energy industry has now developed reliable and cost competitive systems using a variety of technologies. In a report, India's gross renewable energy potential (up to 2032) is estimated at 220 GW. It is likewise noted in the report that, with a renewable energy capacity of 14.8 GW (i.e. 9.7% of the total installed generation capacities of 150 GW as on 30 June 2009), India has barely scratched the surface of a huge opportunity. However, in the last couple of years itself, the share of renewable energy in installed capacity has grown from 5 to 9.7% (The Economic Times, 2009). This implies an enormous potential in energy generation, which can achieve several hundred GW with current renewable energy technologies. As the cost of building solar PV–wind capacity continues to fall over the next five to ten years; a significant scale-up of renewable generation is a very realistic possibility in the developing world. Thousands of villages across the globe are still being exiled from electricity and energizing these villages by extended grids or by diesel generators alone will be uneconomical. Moreover, with the current resource crunch with government, these villages receive low priority for grid extension because of lower economic return potential. Standalone solar PV–wind hybrid energy systems can provide economically viable and reliable electricity to such local needs. Solar and wind energy are non-depletable, site dependent, non-polluting, and possible sources of alternative energy choices. Many countries with an average wind speed in the range of 5–10 m/s and average solar insolation level in the range of 3–6 KWh/m^2 are pursuing the option of wind and PV system to minimize their dependence on fossil-based non-renewable fuels (Bellarmine & Urquhart, 1996; Nayar, Thomas, Phillips, & James, 1991). Autonomous wind systems (in spite of the maturity of state-of-the-art) do not produce usable energy for a considerable portion of time during the year. This is primarily due to relatively high cut-in wind speeds (the velocity at which wind turbine starts produces usable energy) which ranges from 3.5 to 4.5 m/s. In decree to overcome this downtime, the utilization of solar PV and wind hybrid system is urged. Such systems are usually equipped with diesel generators to meet the peak load during the short periods when there is a deficit of available energy to cover the load demand. Diesel generator sets, while being relatively inexpensive to purchase, are generally expensive to operate and maintain, especially at low load levels (Nayar, Phillips, James, Pryor, & Remmer, 1993). In general, the variation of solar and wind energy does not match the time distribution of the demand. Thus, power generation system dictates the association of battery bank storage facilities to overcome/smoothen the time distribution-mismatch between the load and renewable (solar PV and wind) energy generation (Borowy & Salameh, 1996). A drawback common to wind and solar system is their unpredictable nature and dependence on weather and climatic change. Both of these (if used independently) would have to be oversized to make them completely reliable, resulting in an even higher total cost. However, a merging of solar and wind energy into a hybrid generating system can attenuate their individual fluctuations, increase overall energy output, and reduce energy storage requirement significantly. It has been shown that because of this arrangement, the overall expense for the autonomous renewable system may be reduced drastically (Bagul & Salameh, 1996). Nowadays, the integration of PV and wind system with battery storage and diesel backup system is becoming a viable, cost-effective approach for remote area electrification. Wind and solar systems are expandable, additional capacity may be added as the need arises. Moreover, the combination of wind and solar PV system shrinks the battery bank requirement and further reduces diesel consumption. The prospects of derivation of power from hybrid energy systems are proving to be very promising worldwide (Beyer & Langer, 1996; Erhard & Dieter, 1991; Seeling-Hochmuth, 1997). The use of hybrid energy systems also reduces combustion of fossil fuels and consequent CO_2 emission which is the principle cause of greenhouse effect/global warming. The global warming is an international environmental concern which has become a decisive factor in energy planning. In wake of this problem and as a remedial measure, strong support is expected from renewables such as solar and winds (Diaf, Notton, Belhamel, Haddadi, & Louche, 2008). The smart grid readying is associate optimum resolution to the present-day power sector issues like environmental pollution caused by typical power generation, grid losses, as well as poor reliableness and accessibility of power in rural areas (Zaheeruddin & Manas, 2015). The PV–wind hybrid energy system using battery bank and a diesel generator as a back-up can be provided to electrify the remotely located communities (that need an independent source of electrical power) where it is uneconomical to extend the conventional utility grid. All possible advantages of a hybrid energy system can be achieved only when the system is designed and operated appropriately (Gupta, Kumar, & Agnihotri, 2011). In these systems, sizing, control setting, and operating strategies are interdependent. In addition, some of the system components have non-trivial behavior characteristics.



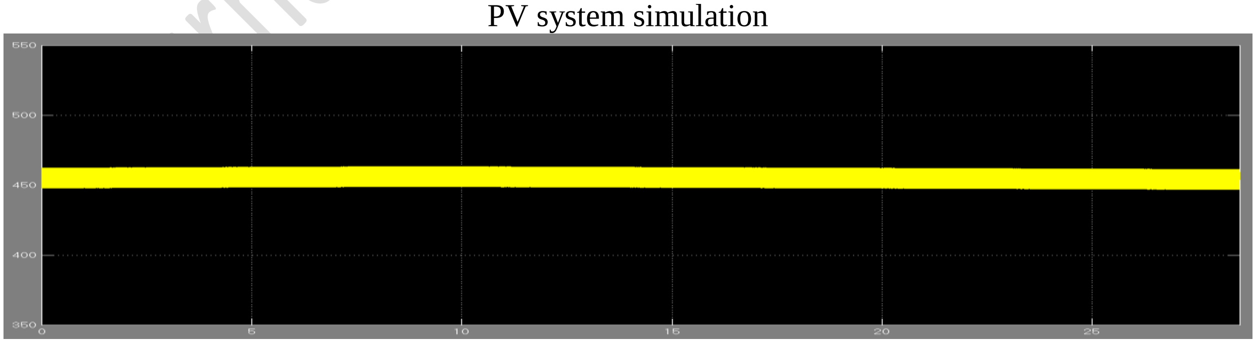
Proposed renewable energy system configuration



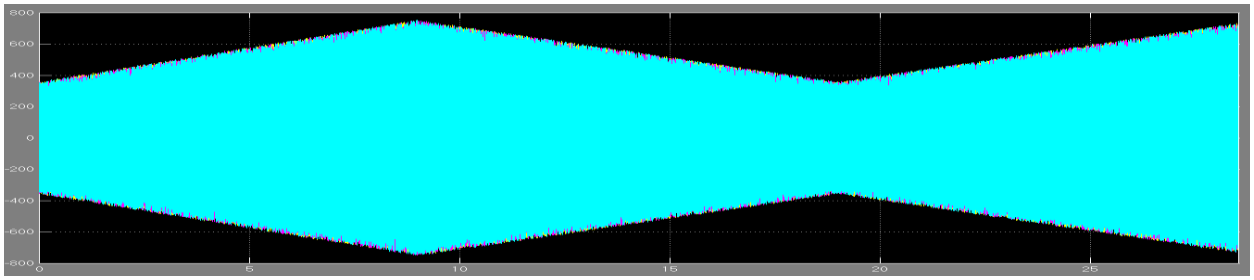
Wind energy system simulation



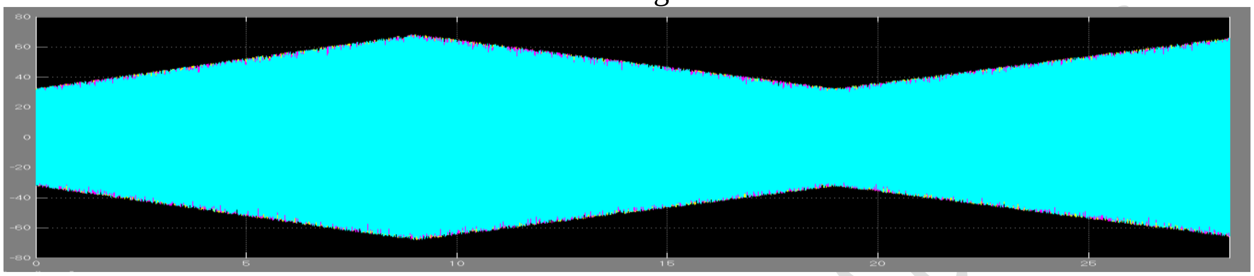
PV system simulation



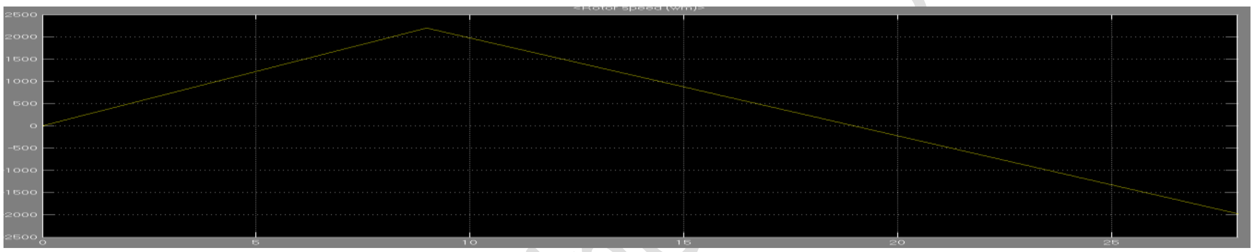
Cluster voltage vs time



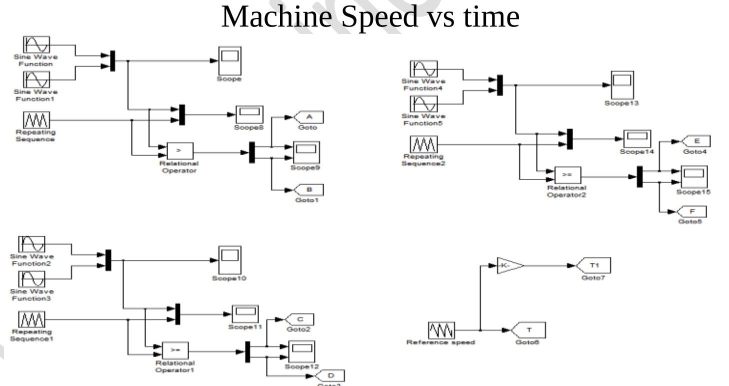
Machine voltage vs time



Machine across current vs time



Machine Speed vs time



Controller for the proposed circuit configuration

CONCLUSION

The renewable operated modular multilevel converter (MMC) has emerged as a suitable topology for high power drive applications. However, the voltage fluctuations of its floating capacitors increase the control complexity of the converter. In this project, the RES fed MMC dc-port voltage is manipulated to regulate the amplitude of these fluctuations to a constant value during the whole frequency range. The proposed approach has several advantages when compared with the conventional ones since it minimises the voltage fluctuation in the capacitor cells. Additionally, it decreases the common-mode voltage at low frequencies and the capacitor rms current, increasing their expected lifespan and reducing the winding insulation damages and the leakage currents in the bearing of the machine. The effectiveness of the proposed control strategy is validated with a laboratory-based prototype composed of 18 power cells, feeding a vector-controlled induction machine.

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