

# Design an Asymmetrical Nine-Phase Electric Drive and Fast Battery Charger for Electric Vehicles

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**ABSTRACT:** This paper proposes an integrated on-board charger for electric vehicles (EVs) that incorporates an asymmetrical nine-phase machine and an inverter into the charging process. The charging is from three-phase mains, and it employs exclusively the power electronic components that already exist on-board the vehicle, and that are mandatory for the propulsion. Moreover, the charging is achieved without any hardware reconfiguration since the existing elements and their connections are not altered during the transfer from propulsion to the charging mode. Instead, the operating principle is based on additional degrees of freedom that exist in nine-phase machines. These degrees of freedom are employed to avoid electromagnetic torque production in the machine during the charging process, although currents flow through its stator windings. The configuration operates with a unity power factor and is capable of vehicle-to-grid (V2G) operation as well. A detailed theoretical analysis is given, and the control for the charging/V2G and propulsion modes is discussed. Theoretical analysis is validated by experiments for charging, V2G and propulsion operating regimes.

**KEYWORDS:** On-board Charger, Electric Vehicle, Nine-phase Machine, Vehicle-to-Grid, SVPWM Inverter.

## I. INTRODUCTION

On-board chargers are a valuable part of EVs as they liberate drivers from the dependency on fast dc charging stations. At present it is common that chargers for EVs are made as separate units when they are placed on-board. Compared to a vehicle without an on-board charger, these units have a negative impact on the cost, weight and spare space in the vehicle. However, power electronic components that form a typical on-board charger do not differ from the elements that already exist on-board and that are required for propulsion. This fact is the origin of the three decade old idea that existing power electronic components can be integrated into the charging process. Many proposals for integration have been reported since. The study performed in shows that the vast majority of EVs have a propulsion motor of either induction or permanent magnet type. Although several integrated single-phase solutions have been proposed for these types of machines, they are only applicable for slow charging due to the limitations of a single-phase grid. In order to achieve a fast charging either a dc charging station or a three-phase ac grid has to be employed. For the former option the driver has to consider the charging station distribution, and to plan the route accordingly. Unlike dc charging stations, three-phase grid is widely available. Nevertheless, at present only few configurations allow fast integrated charging incorporating an induction or permanent magnet motor. Moreover, some of them require a mechanically locked rotor as there is a torque production in the machine during the charging process. This leads to numerous problems with regard to efficiency, increased wear, and audible noise. Only four of the solutions have the advantage of torque-free three-phase charging. In a three-phase machine in an open-winding configuration, supplied from a triple H-bridge inverter, and is considered for the integration into the charging process. In the charging mode the three-phase grid is directly connected to mid-points of each of the three machine's stator phase windings. The charging process is controlled in such a manner that the same currents flow through the two half-windings of each phase. As the half-windings are in spatial opposition the winding does not produce a field in the rotor. Since standard three-phase

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machines do not have access to their winding mid-points, the machine has to be custom made – in essence it has to be a symmetrical six-phase machine. The topology has a great advantage that it does not require any hardware reconfiguration between the propulsion and the charging mode of operation. The solution is currently being considered for use in future EVs by Vale.

The first fast integrated charger that found its way into commercial EVs is the one used in Renault ZOE. Its 43kW “Chameleon” charger can charge 80% of the battery capacity in thirty minutes. The inverter and synchronous motor with excitation winding, which are used for propulsion, are incorporated into the charging process. However, the charger also requires a junction box which is a non-integrated element. Its function is to manage the charging process, to convert the alternating current into direct current and to communicate with the charging station. The charging process is without a torque production in the machine, but an additional power electronic converter is required. A configuration incorporating an asymmetrical six-phase machine is considered in it, also operates without torque production and utilizes the principle of phase transposition hardware reconfiguration is required. A topology that does not require any hardware reconfiguration between the operating modes was introduced in at a basic theoretical level. It integrates a nine-phase machine with three isolated neutral points into the charging process. In the charging mode the three-phase grid connections are directly attached to the three isolated neutral points of the machine. The configuration is controlled in such a way that the same currents flow through all windings belonging to the same three-phase set, so that the field is cancelled within the set itself. The control in was based on only the fundamental grid current control in charging mode, propulsion mode was treated only at a conceptual level V2G mode was not addressed at all, and theory was underpinned by simulation results only.

The work of is advanced by providing a detailed description of an improved control system for the charging mode that includes low-order current harmonic control. The operation is also extended to V2G mode. Next, control for the propulsion mode is fully developed as well, including current control in all the relevant planes of the nine-phase system. Last but not least, the concept is fully verified experimentally, by providing test results for the charging, V2G and propulsion modes of operation. The application of multiphase systems is explored in electric power generation, transmission and utilization. The research on multiphase generators has recently started. The research on multiphase drive systems has been significantly developed since the beginning of this century due to advancement in semiconductor devices and digital signal processors technologies. It is to be emphasized here that ac/dc/ac converters generally supply the multiphase motors. Thus, the focus of the current research on multiphase electric drives is limited to the modeling and controlling of the power converters. Little effort is being made to develop static multi winding transformation system to change the phase number from three-to-9-phase. An exception is where a new type of transformer is presented, which is three phase-to-nine-phase system. The analysis and design, however, are completely different. The control methods to test the motor, which are available to lower the current distortion based on application and requirement. The machine parameters obtained using a PWM inverter or any other method may not provide the correct value. Therefore, a pure sine wave supply system is required to feed the motor for better analysis. Accordingly, this paper proposes a special transformer /multi winding transformer connection scheme to obtain a balanced three-to-nine-phase supply with sinusoidal waveforms. The expected application areas of the proposed transformer are the electric power transmission system, power electronic converters, aerospace, railway and automobile applications and the multiphase electric drive system.

A theoretical analysis of the charging process incorporating an asymmetrical nine-phase machine is given. Complete control algorithms for the charging, V2G and propulsion modes are presented. Experimental results for the charging, V2G and propulsion modes are given in Section V. The use of no of phase systems compared to three phase systems has brought about researchers interest.

## II. RELATED WORK

In papers [1]-[6], multilevel inverters have been widely applied in high-power applications. Among multilevel inverters, the NPC inverter has the most widely used topology because of its advantages. The NPC inverter improves

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the output voltage and current waveforms and can reduce the size of the filters. In addition, the voltage stress across the switch is reduced to half that of a conventional two-level inverter. It is composed of twelve IGBTs and six diodes. The DC-link capacitor is split into two sources to generate different voltage levels. In paper [7]-[11], to maximize the performance of the NPC inverter, the voltages of the two capacitors connected in series must have the same values. If these values are different, this may lead to premature failure of the switching devices, and the THD of the output current increases because the low-order harmonics become dominant; and second- and fourth-order harmonics appear in the output voltage. Hence the dwell time of a small voltage vector should be divided equally. Conversely, if the dwell times of the P-type and N-type small voltage vectors are adjusted when the neutral point voltage is unbalanced, the neutral-point voltage can be balanced.

In papers [12]-[15], the multilevel inverters have many advantages than two-level inverters like low harmonic distortion of the ac currents, low switching losses, less blocking voltage of the switching device. But it has the disadvantages like the increased number of switching devices and the complex control algorithm. To control multilevel converters, the pulse width modulation (PWM) strategies are the most effective, especially the space vector pulse width modulation (SVPWM) one, which has equally divided zero voltage vectors describing a lower total harmonic distortion. Traditionally, three phase voltage is transformed reference voltage vector, the angle and amplitude of reference voltage vector is used to calculate the duration-time of voltage vector. But, as the level is increasing, the control algorithm becomes more and more complex. In papers [16]-[18], the dwelling time of vector calculation is derived from two-level inverter. By using a linear transformation, the dwell time of vectors for two-level VSI can be transformed for multi-level VSI. A novel classification of voltage vectors is proposed to determine switching pattern of PWM sequence and more complex. An intrinsic relationship between multi-level and two-level is developed and by using a linear transformation, the switching time of vectors for two-level inverter can be transformed for multi-level inverter. A novel classification of voltage vectors is proposed to determine switching sequence.

In papers [19]-[22], in order to study electronic converters for PV systems, one first needs to know how to model the PV device that is attached to the converter. PV devices present a nonlinear V-I characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the PV device may be useful in the study of the dynamic analysis of converters, in the study of MPP tracking (MPPT) algorithms, and mainly to simulate the PV system and its components using circuit simulators. A PV device may be any element that converts sunlight into electricity. The elementary PV device is the PV cell. A set of connected cells form a panel. Panels are generally composed of series cells in order to obtain large output voltages. Panels with large output currents are achieved by increasing the surface area of the cells or by connecting cells in parallel. A PV array may be either a panel or a set of panels connected in series or parallel to form large PV systems.

In papers [23]-[25], multilevel converters are typically considered for high-power applications because they allow operations at higher dc-link voltage levels, avoiding the problems of the series interconnection of devices. It has been recently reported that they present better efficiency than other alternative topologies. Moreover, they can also be interesting for medium- or even low-power/voltage applications because they allow operations with lower voltage-rated devices, which is with potentially better performance/economical feature. Among these topologies, the three-level three-phase neutral point-clamped (NPC) dc-ac converter is probably the most popular. The application of conventional modulation techniques to this converter causes a low frequency (around three times the fundamental frequency of the output voltage,  $f_o = 1/T_o$ ) oscillation of the neutral-point voltage. This, in turn, increases the voltage stress on the devices and generates low-order harmonics in the output voltage. There have been many efforts to analyse this problem and define a modulation strategy to solve it, thereby eliminating the need to significantly increase the dc-side capacitance to minimize the voltage oscillation. a closed-loop control scheme for the three level three-phase neutral-point-clamped dc-ac converter using the optimized nearest three virtual-space-vector pulse width modulation, which is a modulation that produces low output voltage distortion with a significant reduction of the dc-link capacitance.

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In papers [26]-[28], the dc link capacitor voltage in the NPC inverter has to be controlled. In the case of two back-to-back connected NPC converters, the two converters can share the task of balancing voltages on the dc-link capacitor. However, such improvement strongly depends on the modulation indices and power factors of the two converters at the operating point. The dc link capacitor balancing using SVM is an attractive feature as it has a number of redundant states for the implementation of the balancing algorithm and it is suitable for improving the DC link utilization, reducing commutation losses. Some multilevel carrier PWM can be implemented using a single counter. The most attractive approach is to modify the inverter switching Pattern according to a capacitor control strategy to balance NP voltages. In papers [29]-[30], presents a generalized implementation of the 3-level SVPWM technique and investigation of the imbalances in the D.C-link capacitor voltage in Three Level Neutral point diode clamped (NPC) multilevel inverter (MLI), which is one of the main drawbacks of NPC multilevel inverter. The redundant state guarantees to achieve voltage balancing up to 0.75 % with no requirement of any additional control effort. VHDL language is used to model the inverter switch.

### III. SYSTEM IMPLEMENTATION

A. Block Diagram:

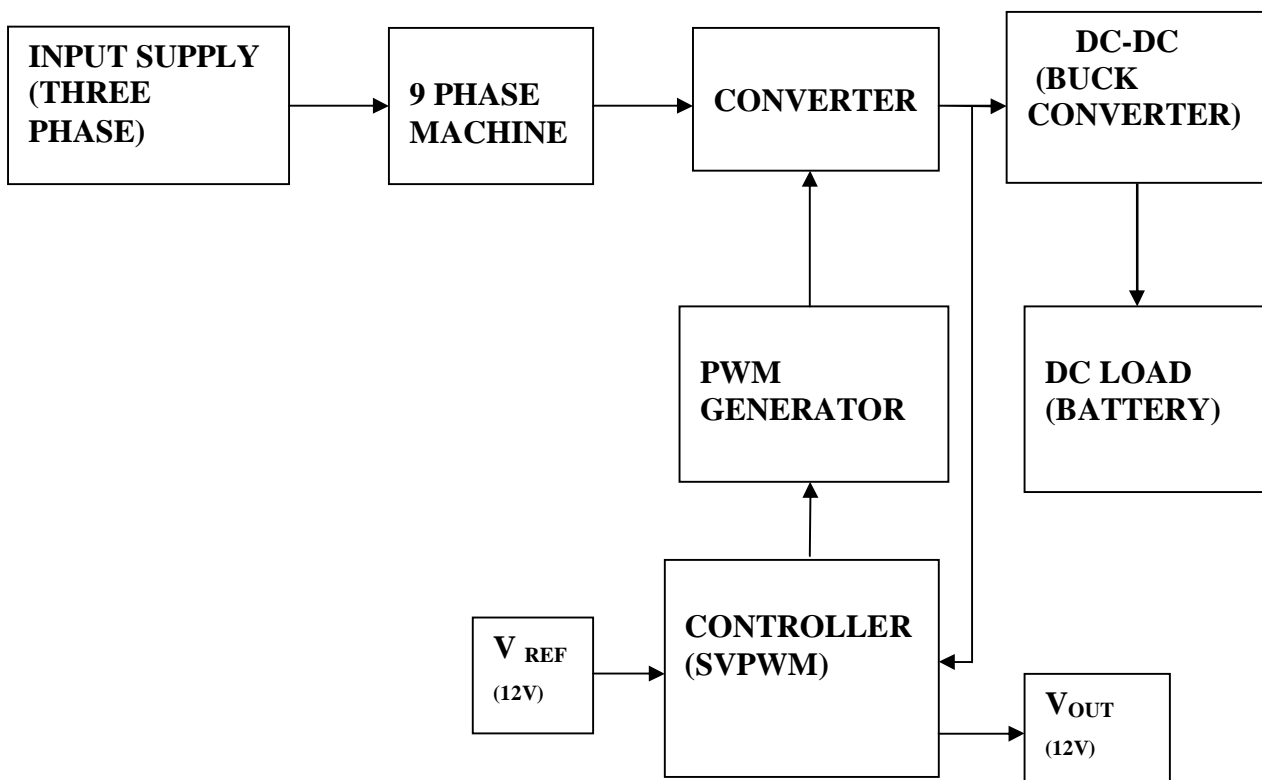


Fig. 1. Block Diagram of the Proposed System

Three phase supply is available in the generating station or grid, were as nine phase supply is required for many industrial applications such as, aerospace, railway and automobile applications. The block diagram of the proposed system was shown in Fig 1. There are different methods in which we can convert 3 to 9 phase using 18-Pulse Converter, Carrier Based PWM Technique, multilevel converter and Multiphase Transformer. The above said methods which are more complicated to design for higher ratings or a pure sine wave will not be obtained or harmonics will be

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more. For Multiphase power transmission system multiphase transformers are needed. In the multiphase power transmission and multiphase rectifier systems, the number of phase can be designed and developed in multiples of three. Therefore, the variable speed multiphase drive system considered in the literature are mostly of five, seven, nine, eleven, twelve, and fifteen phase. So, there is a need to design and develop special transformer which converts from 3 to 9 phases for different arrangement of input and output. Thus, with the proposed technique, a pure nine-phase sine-wave of fixed voltage/current and frequency is obtained, which can be used for RL load and motor testing purposes. Complete design and simulation of the proposed solution is presented.

## IV. SIMULATION MODEL AND RESULT

### B. SIMULINK DIAGRAM:

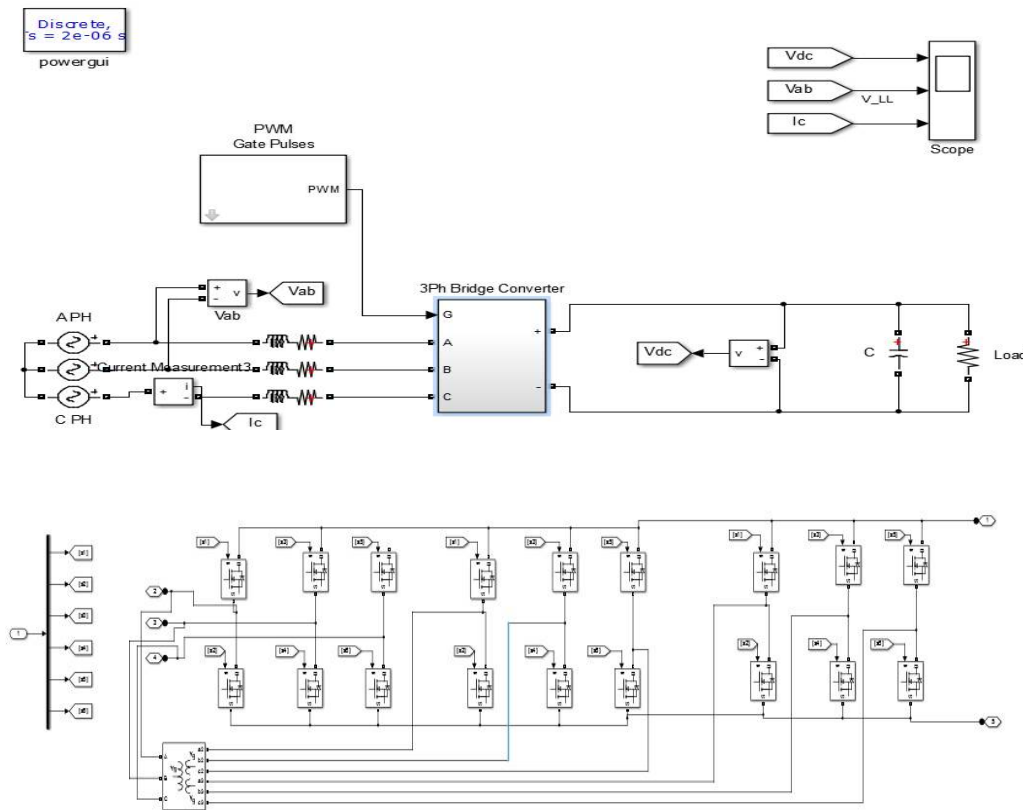


Fig. 2. Simulink Diagram of the Proposed System



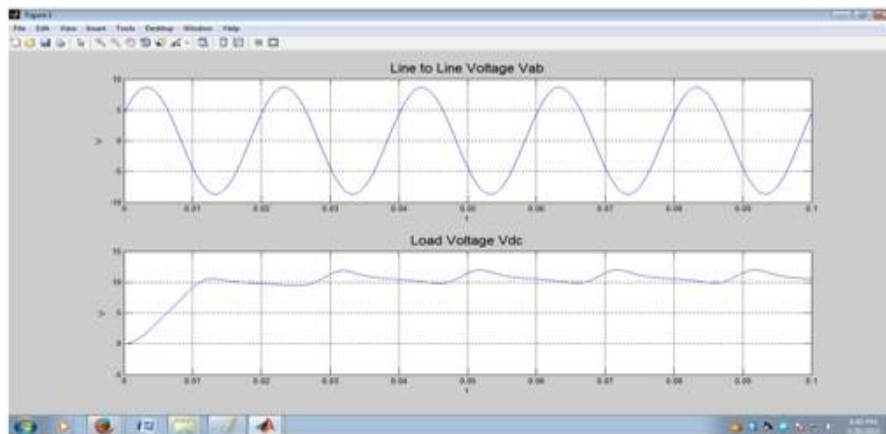


Fig. 3. Simulink Result of the Proposed System

Fig 2 shows the simulation diagram of the proposed system. It can be seen that it is practically constant about 2.13 A, with hardly any ripple. The speed is kept at zero naturally, meaning that there is no torque developed; this is also evident from Fig. 3, where  $\alpha$ - $\beta$  current components have zero value throughout. As discussed in the earlier chapter, the control algorithm for the charging and V2G modes is based on the assumption that three phases of any of the three three-phase windings have identical parameters, leading to the equal distribution of one grid phase current into three currents of the machine. To prove that this is indeed the case here, Fig.3 shows the currents of the three phases of one three-phase winding during charging, for the operating conditions described earlier.

## V. HARDWARE IMPLEMENTATION AND RESULT

### C. HARDWARE CIRCUIT DIAGRAM AND RESULT:

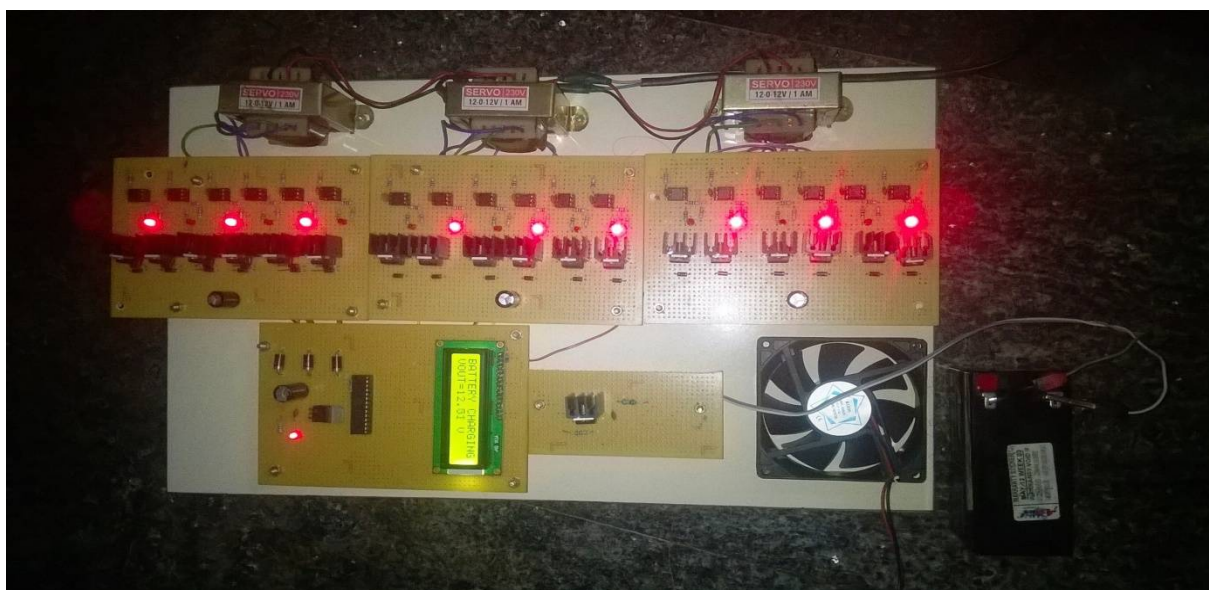


Fig. 4. Hardware Result of the Proposed System

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The hardware result shows in Fig.4 that in the propulsion mode, the grid is disconnected. Hence, the three neutral points of the nine-phase winding are floating, and the system behaves as having three isolated neutral points. The decoupling transformation matrix for an asymmetrical nine phase system with three isolated neutral points is governed with the battery charging of 12V was achieved.

## VI. CONCLUSION

This paper has introduced a novel solution for the fast integrated onboard charging of EVs. The proposed configuration is based on the application of an asymmetrical nine-phase machine. It has the advantages of unity power factor operation and zero average torque production in the machine during the charging mode. Moreover, no hardware reconfiguration is required between the propulsion and charging/V2G modes of operation. Stator leakage inductances of the machine are used to ensure filtering during the charging/V2G operation. The theoretical viability of charging/V2G without torque production is examined, and control algorithms for the charging, V2G, and propulsion modes of operation are given. The presented control scheme is well suited to the situation in which there are no asymmetries within each individual three-phase winding. If this is not the case, an additional current balancing control algorithm would be required in practice. The theoretical values are obtained and verified by the experiment results.

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