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A Neural-Guided Three-Phase Photovoltaic Charging Framework for the Elevation of Power Quality in Modern Electromotive Infrastructures

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***Abstract*— This report presents a better design of an electromotive charging station where a single stage photovoltaic array will be in smooth connection with a three-phase grid via Artificial Neural Network (ANN)-based supervisory control. The proposed system will enhance the quality of power and permit the two-way energy flow between the car and the utility supply. The ANN controller is trained under different operating conditions and thus, the active and reactive power are managed with greater accuracy, resulting in minimised harmonic distortion, voltage stabilisation, and ease of change between grid-connected and islanded operation. The system is higher performance and less structural complexity by removing the requirement of supplemental boost converters and an ingenious estimation of in-phase and quadrature templates. The results indicate that the ANN control improves the tuning challenges, keeps the DC-link stable as well as achieves significant improvements in the event of disturbance, thereby making the charging station more resilient and able to fit the contemporary renewable-infested networks.**

***Index Terms*— ANN control, power quality, photovoltaic charging, three-phase grid, harmonic mitigation, bidirectional flow, voltage regulation.**

I. Introduction

The high rate of electrification of transport has resulted in a significant transformation of energy production, regulation, and distribution of modern power systems. The necessity to have efficient, reliable, and power-quality-friendly charging points has been increasing in importance as the electric vehicles (EVs) gain popularity in various spheres of the society. Early studies in renewable-powered charging, which combined solar and wind plans to recharge vehicle batteries provided important information in self-sufficient charging techniques and effects on harmonic action and energy utilization [1]. But these early systems invariably relied on standard single direction chargers and so there was no prospect of EVs to communicate with the grid in any complex fashion. Rapid off-board charging Technological advances into use of resonant converters and flexible rectifier architectures were pursued to accommodate a wide battery capacity range and minimize power losses and switching stresses, hence establishing the environment of stable charging bases [2]. Parallel to these electrical advances, comparable advances were made in the field of circuit-based approaches to charge batteries and to control motors with high-efficiency DC to DC converters and supervisory microcontrollers [3].

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Although such configurations proved effective in the field that they were designed to operate in, it was discovered by the developers that such conventional control mechanisms had limitations, particularly in the situations where loads were changing or non-linear behaviors would occur. The improvements of the vehicle-mounted converters including interleaved LLC resonant structures that can transfer wide voltage ratios at various operating conditions demonstrated additional opportunities of the performance improvement step and implied the importance of flexible modulation at alternative operation conditions [4]. Meanwhile, the introduction of a bidirectional single-phase charger with reactive power capabilities also indicated the growing understanding that EVs cannot be viewed as a load, but they can also be looked upon as a possible stabilizer that could be used to ensure grid stability through reactive exchange [5].The expansion of V2G and G2V functions gave rise to new converter structures to achieve higher voltage gain, smoother bi-directional circulation and improved dead-beat regulation to achieve rapid response to current [6]. The frequency-adaptive control of three-phase four-leg inverters studies offered a solution to the controlling of correct current after even under unbalanced voltages or varying grid frequencies thereby enhancing V2G operation power injection correctness [7]. The investigations in the context of microgrids, in particular, the isolated or military-based ones, demonstrated the benefit of distributed storage that involves EV batteries as a backup to avoid the problem of stability and over-generating cycling [8]. At the same time, unresolved issues with the reactive power compensation and minimization of power losses gave rise to a new understanding of optimized capacitor placement and smart allocation algorithms [9], thereby creating the implementation of a broad-range adaptation approach to power-quality control. The aspect of cost also entered the discussion when academics had to analyze the possibility of the implementation of coordinated charging and discharging policies of the commercial estates that through the intelligent planning of the EV energy exchange could reduce the electricity bill and unload the grid during the peak-hours [10].

II. Literature Review

The controversy about the possibility of battery electric vehicles (BEVs) charging being both energy and cost-efficient due to the incorporation of renewable energy has evolved over time. It has been started by studies that were made on the integration of photovoltaic and wind systems to recharge the automotive batteries autonomously, where the studies outlined the effects on harmonic distortion, charge effectiveness, and the range covered by traveling [11]. Subsequently, there have been advancements in works off-board charging architecture and adding resonant converters and flexible rectification configurations sprinkling a wide range of battery voltages and also enabling soft-switching performance and reducing energy wastage [12]. Along that, additional research has been conducted in order to co-locate the charging and motor-control functions by making use of high-efficiency DC-DC converters driven by microcontrollers, therefore, the paper is dedicated to the problems of nonlinear loads and unexpected variations of current draw [13]. Such advances have shown other possibilities of power quality improvements in the systems of the vehicle in particular the research on on-board converter design, especially in the development of LLC resonant structures with wide voltage-transfer ratio [14]. Meanwhile, the studies of bidirectional chargers have shown that they could provide reactive power and work in any quadrant of active reactive plane, hence, accepting the potential of EVs as a new category of grid participants [15]. In addition, vehicles-to-grid (V2G) connection has been expanded due to bidirectional converters with higher voltage gain and dead-beat control, frequency-adaptive repetition control methods have enabled current tracking and harmonic suppression in three-phase four-leg inverters under variable grid operating conditions [16],[17]. In addition to pure converter development the role of the electric vehicles as an asset in microgrids particularly in situations where there is distributed storage that could help reduce the cycling of the generators and hence help the fuel efficiency has been a topic of research that has captured the interest of many theorists [18]. Similarly the problem of reactive power supply and voltage improvement by optimal capacitor localization was also greatly researched on and evolutionary and bio-inspired optimization techniques were found to be useful in distribution networks [19]. The high-energy V2G and vehicle-to-building (V2B) strategy element has entered the academic discourse, and it has revealed the opportunity to introduce scheduled charging and discharging processes in order to reduce the cost of electricity in various tariff systems [20].

III. Proposed System

The suggested system is the result of a harmonious partnership of a photovoltaic array, a bidirectional converter, a voltage-source inverter, and an ANN-guided controller, which will be controlled in a single-stage installation that seeks to simplify structure and, at the same time, enhance power quality. The PV array connects directly to the DC-link, and therefore the necessity to use an intermediate boost converter is avoided and it is guaranteed that the solar harvest can be channelled to power electric-vehicle charging with a minimum conversion loss. The output of the power is to the DC-link where it is fed off to the EV battery or to the utility grid when the sun is shining on the array. The DC-link therefore turns out to be the primary energy storage, which needs to be tightly controlled to ensure that the changes in voltage occurring due to variations in the irradiance do not pose a threat to the stability of the battery or the grid. The ANN controller performs this constant surveillance, the primary purpose of which is to provide harmony among the numerous interacting elements of the system.

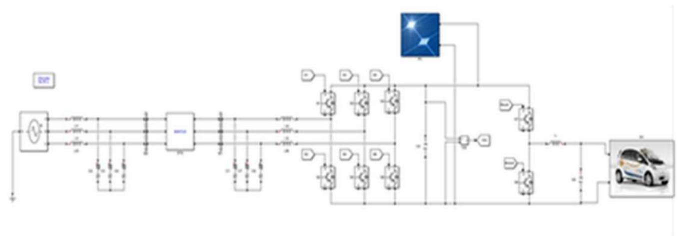

Figure 1. diagram of Three-phase Three wire single-stage grid connected PV system with EV

As shown Figure 1, the Simulink diagram represents a three-phase, three-wire single-stage grid-connected PV system integrated with an electric vehicle. The system includes a PV source, power converters, and grid interface components for efficient energy transfer. It enables direct utilization of solar energy for EV charging while maintaining grid stability. This configuration ensures improved power quality and efficient energy management.

When the vehicle needs charging in the case; the active power reference is configured to the way the owner wants the car to run. When the owner would require to recharge the battery, the bidirectional converter would switch depending on the instructions of the ANN and thus steal power at a regulated rate via the DC-link. Differently, when the owner desires to unload the battery and feed the grid to receive a reward or a peak load relief, the converter charges the opposite way compelling the vehicle to feed the grid with power. The ANN is another method that predicts change in current flow and the level of voltage in the process and through learning corrects them before they have turned into disturbances. Thus, the converter remains adjustable in its operations, it may be responsive to sudden growth and decrease of load, quick fluctuation of PV power and temporary grid outage.

The voltage-source converter that was connected at the point of common coupling to the grid is the one that performed the required task of transforming the reference currents to such an extent that integration of power through with minimal distortion is being realized. ANN controller The ANN controller used measured grid voltages to calculate in-phase and quadrature unit templates, enabling the system to generate large fidelity active and reactive current components. Then they are converted to the inverter where the gate pulses are produced by a hysteresis modulation plan. This design not only allowed the system to share real power, but also to be able to reactively compensate to the grid, which guaranteed that the voltage could be held and any harmonics that the system emitted into the next circuits could be suppressed. The charging station is going to become not only a consumer of power, but also a protector of electrical quality through this dual service.

The ANN controller identified the in-phase and quadrature unit templates according to the measured grid voltages, and therefore gave the system the capability to generate the active and reactive current components with high precision. These are the currents that are fed to the inverter, the gate pulses of which are obtained by a hysteresis modulation scheme. Such a system also allowed the exchange of real power as well as provided the grid be able to compensate reactive compensation and therefore ensuring the continuity of voltage regulation and preventing the emittance of the harmonic components that were otherwise propagated to the other circuits. Through this dual function, the charging station thus does not only remain a consumer of power but also a guardian of electric quality. The statistics that the mock-up exercises gave out are quite eloquent as regards to the efficiency of the proposed ANN-controlled photovoltaic charging station where the single-stage setup proves to be much more stable than the traditional ones. The DC-link voltage remains highly stable under different irradiance conditions, with its variation being restricted since the ANN controller is a fast inferential controller. Overshoots tended to occur whenever the sunlight rose or fell suddenly, but the ANN, having the capability to identify fresh patterns in the evolving input, did so with extreme caution before the error magnitudes were so great. The resultant voltage profile was therefore reduced in number of ripples, reduced settling time as well as increased uniformity. the stability, in particular, is very significant since the DC-link is the switching point that both grid and vehicular loads are acting on, and its saving results in significant savings of battery and converter life.

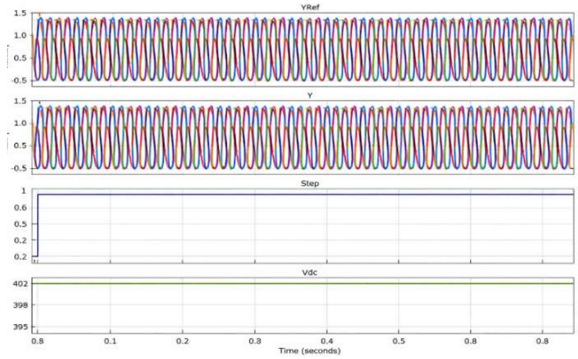

Figure 2. Simulation results of Charging Station at Steady State

As shown in Figure 2, the simulation results of the charging station at steady state illustrate balanced three-phase waveforms for reference and output signals. The system maintains stable operation with consistent voltage levels and minimal fluctuations. The DC link voltage remains constant, indicating effective power regulation. This demonstrates reliable and efficient steady-state performance of the system.

Another way it also displayed its excellence was the fact that the system was capable of fine-tuning the reactive power and minimizing the harmonics. The ANN-controlled inverter was highly precise in tracking the reference currents, thereby generating an intense reduction of the overall harmonic distortion, in the instance of unbalanced loads and voltage sags. Under usual conditions, when the grid voltage is distorted or asymmetric, controllers based on fixed mathematical relationships do not vary their settings very fast. Contrary to that, the ANN updated its existing approximation of the internal interactions of the system to modify its instructions in real time, therefore, enabling the inverter to be able to remove the additional harmonic content even when the supply conditions were unfavorable. The grid current waveform was therefore still near to sinusoidal and the reactive power injected was flowing softly hence the power factor at the utility node was in the acceptable range.

Figure 3. (B) Grid current THD%

As shown in Figure 3, (B) the grid current THD analysis illustrates the harmonic components present in the system. The FFT spectrum shows a dominant fundamental frequency with relatively lower harmonic magnitudes. The THD value is maintained within acceptable limits, indicating good power quality. This demonstrates the effectiveness of the control strategy in reducing harmonics.

The system as an example was very good in its manner on how the system can maintain a balanced three-phase voltage waveform despite disturbances in the local loads. The inverter assumed the voltage source within a very short period of time, therefore, supplying the loads with the necessary voltage and frequency at a time when the grid was dropped. ANN was a crucial element that assisted in compensating the sudden load current fluctuations that might have led to the reduction of the islanded waveform with a high degree of distortion. The station could only be stabilized after the synchronization algorithm put the phase, magnitude and frequency within tolerance and the station was returned to the utility supply. Therefore, it kept the system safe against the reconnection bursts, and ensured the switching between the islanded and the grid-connected state was seamless and the load and battery did not visibly relax.

TABLE I: COMPARISON OF GRID CURRENT THD% BETWEEN EXISTING SYSTEM AND EXTENDED SYSTEM

	Existing System	Extension System
Grid Current THD%	2.78%	0.45%

A combination of these results in Table.1 suggests that the ANN-controlled charging station as suggested is a stronger, more adaptive, and power-quality-conscious solution to the grid as compared to traditional ones. The capability of the ANN to detect, predict and correct deviations makes it highly beneficial in diverse environmental as well as operational circumstances. The ability to achieve the performance of the entire system, including more stable DC-link voltage, better harmonic mitigation, and correct active and reactive power exchange, as well as smooth transitions between grids and island, demonstrates the potential of intelligent control as one pillar of the next EV infrastructure. The proposed system can address the growing needs of the electrified transport networks of the future because it combines renewable generation, sophisticated power electronics, and neural intelligence.

IV. CONCLUSION

This paper has demonstrated that the synergies that follow between photovoltaic production, bidirectional power flow and an ANN controlled structure are an exceptionally robust and a future-ready charging design in the electrified transport industry. Since the system proposed is capable of maintaining the DC-link in a stable condition, managing the harmonic distortions, and properly managing the active and reactive currents, the system is then significantly a much better system compared to the traditional tuned ones. Its applicability depends on the features that it must possess to predict the disturbances, sustain the voltage when the irradiance suddenly changes, and the easy transition to the grid-connected mode as well as the islanded mode. Along with this, intelligent learning allows the converter to continuously adapt to the changing conditions whereby it does not require a human intervention to recalibrate the converter. Thus, the system can be regarded as a possible solution to the next-generation EV infrastructures with renewable energy, grid stability, and adaptive control having to coexist to provide the effectiveness, stability and power quality, in the ever more complex electrical network, to continue.

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