System Modelling of Electric Vehicles Charging Infrastructure using Micro-Turbine Generator

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Abstract

Climate change is significantly affected by the increase of greenhouse gases produced by burning fossil fuels. The transportation sector is considered one of the major sources of these emissions. A real need to develop an efficient and clean transport system such as electric vehicles (EVs) can play a significant role to reduce greenhouse emissions. However, EVs have several main concerns that are interrelated to each other such as range anxiety, charging time, and lack of charging infrastructure. This study proposes a new design concept of charging infrastructure (IMLEV) for EVs using micro-turbine generator technology combined with lithium-ion batteries (LIB) as an off-grid power source. The charging infrastructure architecture was designed based on system components sizing optimisation to meet the power demand. A multi-physics modelling tool was used to develop the control system and the control strategies. Four different charging demand scenarios were implemented to evaluate the system's ability and showed good results in terms of power delivery and stability in IMLEV.

1. Introduction

The high demand for electric vehicles (EVs) in shortcoming years can potentially lead to issues such as charging time and charging infrastructure. The market survey performed by Woodward et al. [1] also acknowledges that these two concerns are among the top three for the EVs' future ownership. To resolve these issues, more investment has been planned to meet the energy demand. In European Union countries, it is estimated that 1.3 million public charging infrastructure is required by 2025 with €1.8 billion investment [2].

Several works have been carried out to improve the EVs charging infrastructures for solving the range anxiety and the charging time issues by developing several charging methods. Huang et al. [3] develop a model to design a slow and fast charging infrastructure that can meet charging demands. Meintz et al. [4] studied 50 – 120 kW DC fast charging technology based on different vehicle models and understood the impact in terms of charging time, limitation of battery C-rate, the electrical component system design, and vehicle cost. Joy et al. [5] developed a multi-point bi-directional contactless charging system for EVs application. The maximum DC power handling capacity of the system was designed and simulated at 200 kW and analysed for vehicle-to-grid V2G) and grid-to-vehicle (V2V) operations. The same approach was also used by Arancibia and Strunz [6] using a DC fast charging infrastructure for three vehicles with a 50 kW DC power. However, the main difference between the two methods was the 50 kW DC power has reactive power compensation. Khan et al. [7] developed a control system for on-grid charging infrastructure by using a constant current-constant voltage charging scheme to improve the performance of the charging infrastructure by reducing the current harmonic distortion. However, the work did not include the high impact of such designs on the power grid and the issues that can occur throughout peak time.

From the above literature, the charging infrastructures are steered for two approaches, 1) an off-grid EVs charging infrastructure, and 2) a combined charging system using renewable energy sources such as wind and solar energy with the grid source. Based on these concepts, many ideas appeared to design and develop the off-grid or the combined energy charging infrastructures depending on different technologies. For example, wind turbine technology was widely experienced as a renewable and independent power source. Fathabadi [8] proposed a wind energy charging infrastructure with V2G ability and a three-phase bidirectional DC/AC inverter connected to the grid. Xydis and Nanaki [9] presented a wind energy analysis study based on geographic information systems to identify the optimum sites of the wind energy system. The result revealed that the optimum location of the wind energy systems has to be outside the cities, where the power is required for the public charging infrastructures. Also, wind energy systems require a high initial investment, and it may produce noise and aesthetic pollution. Esfandyari et al. [10] used a photovoltaic array that can be combined with battery energy storage to cover the charging demand of EVs. On the other hand, Liu et al. [11] designed a charging infrastructure assignment and power grid impacts assessment in big cities.

Based on all methods proposed using renewable energy sources, it can be concluded that any concept of charging infrastructure adopted has its limitations. Therefore, the integration of all the current methods is required to develop a more robust charging infrastructure solution. The charging demand still needs more effective efforts to find constructive solutions to cope with the increasing EVs demand, which is required to offer a reliable charging service. However, most charging infrastructures that are being used or developed nowadays rely on the electricity provided by the main power grid either totally or partially. This arrangement can be damaging to the main power grid, and the negative impact can be growing in the next few years as a result of increasing charging infrastructures. For all the challenges surrounding the EVs that were explored earlier, this study proposes an off-grid fast-charging infrastructure for EVs by using a new concept of micro-turbine generator (MTG) as a power source combined with a second life lithium-ion batteries (LIB) with a maximum state-of-energy (SOE) of 80%. The work focuses on the requirements in terms of 1) system component sizing for optimum system design, 2) control strategies for peak and off-peak demands using fast charging and slow charging, and 3) system stability.

2. Simulation set-up

Based on the available DC fast charging standard, MTG with 50 kW electrical power output was considered for the charging infrastructure system. A LIB of 50 kW was integrated with MTG to provide fast DC charging for EVs to meet the charging mode 4 standard requirements [12] to resolve the issues with range anxiety and charging time. The power output of LIB was based on 20 – 80% SOE. The architecture of integrated MTG and LIB of EV charging infrastructure (IMLEV) in this work is shown in Figure 1. MTG was considered the primary power source in IMLEV and was mainly used to provide DC fast charging for EV_2 port and AC charging for EV_1 port. IMLEV also provided power to the main grid during off-peak charging demand.

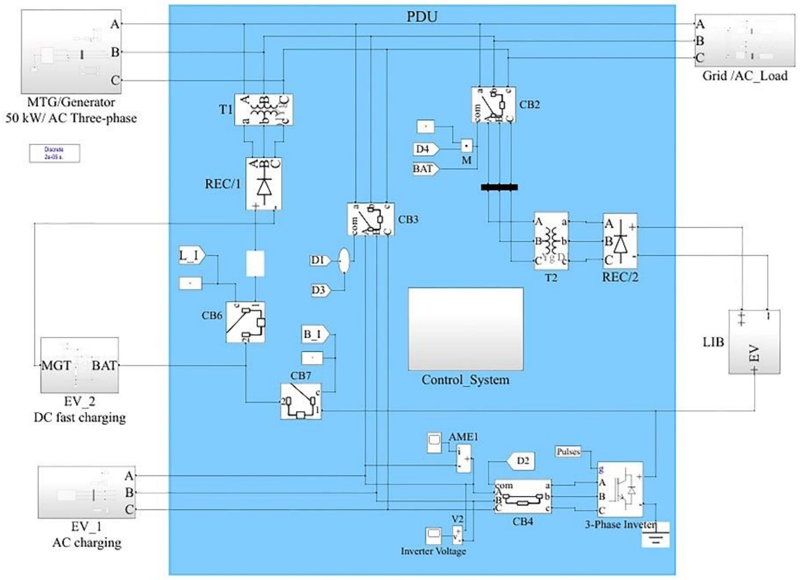


Figure 1. System model of mode 4 IMLEV AC/DC charging infrastructure architecture for peak and off-peak demands

LIB supported IMLEV during peak charging demand and charged by MTG during off-peak demand. Therefore, it was designed to provide DC fast charging and AC slow charging as well as to expand the availability of IMLEV to meet all possible charging conditions. Also, a power distribution unit (PDU) was used to control the performance of IMLEV throughout various operation conditions. The control system has a significant role to manage and control IMLEV based on energy availability and operation conditions to obtain the desired outputs. Since there were several inputs and outputs to PDU, a multi-input multi-output concept was proposed for IMLEV. The primary input was the power supplied from MTG and the secondary power input came from LIB. The outputs consisted of DC fast-charging port, AC charging port, grid load, and LIB charging line. The powers for both AC and DC charging ports were supplied by MTG and LIB.

Table 1 shows four control functions of IMLEV power distribution with an embedded controller using a rule-based function. The outputs of IMLEV were generated by four functions 1) B-1, battery side connection, 2) L-I, DC fast charging side connection, 3) GRID, grid load condition, and 4) BAT, battery status for charging and discharging situation. Also, the outputs pulses of the controller D1, D2, D3, and D4 were used to control circuit breakers. An AC/DC rectifier was employed to provide DC fast charging from MTG directly to the DC charging point and provide LIB with DC charging. Additionally, a DC/AC inverter was used to provide the AC charging point with the required AC power from LIB. Table 2 shows the power strategies of IMLEV for DC fast charging and AC charging. A grid load was simulated to evaluate the robustness of IMLEV in four power strategies.

Table 1. Rule-based function of IMLEV.

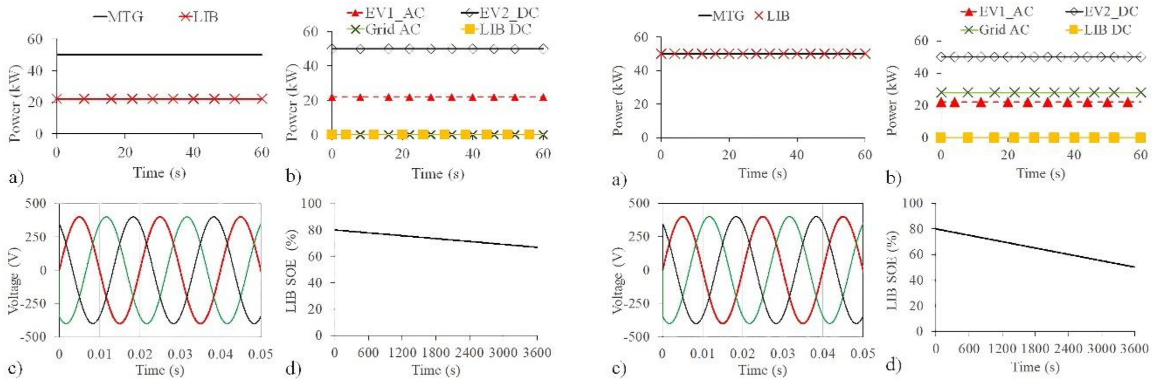
	Conditions	**Parameters**	**Switch**
Function 1	B_I = 0, L_I = 1	B_I > 0, L_I > 1, BAT < 1, GRID < 1	D1 = 0
Function 2	L_1 = 1, B_I = 0	B_I > 0, L_I > 0, BAT < 1, GRID < 1	D2 = 0
Function 3	L_1 = 0, B_I = 0	B_I < 1, L_I < 1, BAT > 0, GRID < 1	D3 = 1
Function 4	L_1 = 0, B_I = 0	B_I < 1, L_I < 1, BAT < 1, GRID > 0	D4 = 0

Table 2. Four steady-state operating power strategies of IMLEV

Power strategies	**EV1**	**EV2**	**Battery charging**	**Battery discharging**	**Grid**
1	On (22 kW) from LIB	On (50 kW) from MTG	Off	On (22 kW) to EV1	Off
2	On (22 kW) from MTG	On (50 kW) from LIB	Off	On	On (28 kW) from MTG
3	On (22 kW) from MTG	Off	On (28 kW) from MTG	Off	Off
4	Off	Off	Off	Off	On (50 kW) from MTG

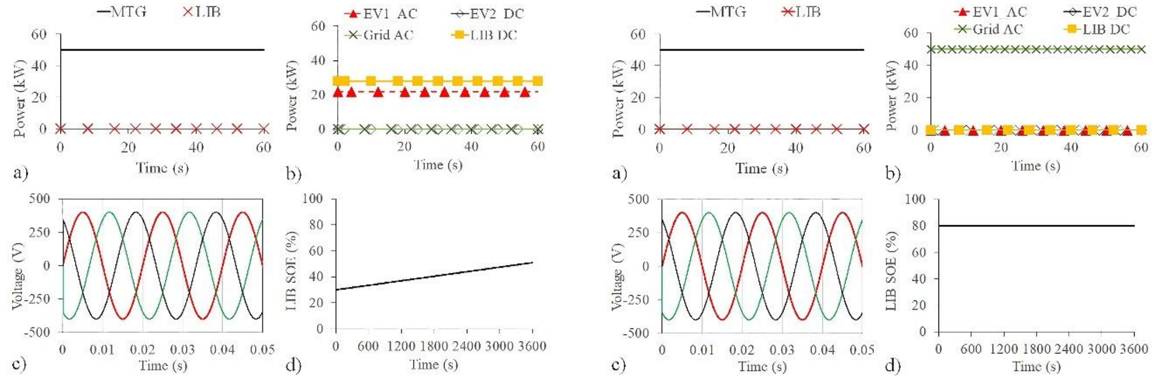
3. Power strategies results

Figure 2 shows the simulated results of power strategies based on peak demand and off-peak demand. All IMLEV power strategies were stable and had no remarkable fluctuations in the system frequency or the system voltage. A negligible amount of fluctuation occurred at approximately ± 0.1% for the initial 0.1 seconds. IMLEV frequencies for 3-phase AC voltage from the simulation was at 50 Hz with ± 400 V. LIB SOE shows energy depleting and charging based on power strategies respectively.



Power strategy 1

Power strategy 2



Power strategy 3

Power strategy 4

Figure 2. Four IMLEV simulations for steady-state power strategies for a) power supply from MTG and LIB, b) EV1 AC port, power output to EV2 DC port, Grid AC, and LIB DC charging, c) system AC voltage, and d) LIB SOE

4. Conclusion

IMLEV model has been successfully validated against steady-state power strategies. The embedded controller worked with IMLEV and produced stability of the system throughout various loads and for all the measured parameters of the system such as power inputs and output, voltage, and LIB SOE. To improve the work, further work will be carried out to study IMLEV at transient-state based on actual power demanded to reflect its performance behaviour, energy consumption, and emissions.

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