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Modeling and Architectural Frame Work of Off-Board V2G Integrator for Smart Grid

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Abstract- The serious environmental concerns and growing oil demands have influenced the development of Electrical Vehicles (EV). The group of EVs can contribute largely to the grid requirements and participate in power transaction in order to meet the load demands. The Vehicle-to-Grid (V2G) helps in maintaining the power system stability for a short duration of time. The Off-Board and On-Board are two types integrators used for connecting EVs to the electric grid. In this paper the Off-Board V2G integrator framework is proposed. The modeling and simulation is carried out using MATLAB/SIMULINK. The V2G (discharging) operation is considered with two EVs connected to the grid.

Keywords EV, Off-Board V2G integrator; V2G.

1. Introduction

The restructuring policy has motivated the private players to participate in power generation and due to this distributed energy resources (DER) such as photovoltaics (PV), wind turbines, microturbine, fuel cell(FC) and internal combustion(IC) engine are integrated to the grid to supply power to the grid [1]. The Vehicles are usually parked for 90%-95% time in parking stations, residential apartments and office buildings. The parked vehicles can be used for connecting to the grid for power transaction. V2G, EV, gridable vehicles (GV) are not only used for transportation but act as connected load and Distributed Resource (DR). V2G support grid requirements and meet the load demands. They can be used for peak shaving and valley filling when connected to the grid. V2G is efficient and effective solution for peak shaving and valley filling in comparison to the other existing methods [2], [3].

The single vehicle can only consume power and may not be appealing but the group of vehicles can make a large difference and support the grid requirements. The EV can be connected to the home known as Vehicle-to-Home (V2H). The aggregator acts as an interface between the grid control center (GCC) and the EV. The GCC sends the information about the power requirements to the aggregator and in turn aggregator sends information to the EVs. The EV owner decides whether to participate in power transaction with grid. The EVs can draw or transfer power amongst them after getting the green signal from the aggregator. This is Vehicle-to-Vehicle (V2V). The group of EVs which take part in power transaction is known as Vehicle –to-Grid (V2G).

The electrification of vehicle fleet will reduce oil demands and lessens the carbon emission. The EVs can be integrated to the grid to sell or buy the power from the grid and the concept is called Vehicle-to-Grid (V2G). The single EV can consume but cannot deliver power to the grid. The group of EVs makes a sizeable difference and delivers power to the grid. The EVs also support the ancillary services like load levelling, voltage regulation, frequency regulation and balancing. The bidirectional charger is essential for the EV to sell or buy power from the grid. Further the bidirectional charger has the direct current (dc) link capacitor which is inherently able to provide the reactive power support to the power grid.

V2G not only serve as transportation tool but act as a controllable load and Distributed Resources (DR). The EV can be connected to home for charging/discharging using the On-Board or Off-Board bidirectional charger. The control scheme and the battery of the EV decide to draw or transfer power to home. This concept of connecting EV to Home is called V2H [4]. The aggregator is an interface between the GCC and the EV. The GCC provides the information about the electricity requirements to the aggregator and in turn the aggregator after receiving the information, communicates with EVs. The aggregator aggregates the EVs and supply or draw power from the grid. The EVs can sell the power to the local grid and aggregator can communicate with both the entities: the GCC and the EVs and distribute the energy among the EVs and this is known as V2V. The EVs can contribute to the grid by selling or buying power from the grid and helps the power grid in maintaining the load demands. The V2G can be used for peak shaving or valley filling and plays a prominent role maintaining the grid stability. The group of EVs can collectively work for V2G operation.

2. Background

The various opportunities and challenges of V2G are articulated in [4] and the existing techniques available for V2G integration are reviewed in [5] and the potential economic benefits of V2G are listed. Willett Kempton, Jasna Tomić are pioneers of the V2G concept and their research articles are serving as base papers for the researchers in this area. In the year 2005 they articulated two papers: first briefed the basics of V2G and the revenue generation associated with it [6] and in the second paper they explained the complexities involved in implementation of V2G [7]. The potential benefit and sustainability of V2G in Smart Grid Environment is discussed in [8] and the detailed conceptual frame work of V2G is presented in [9]. The impact of V2G on distribution grid is discussed in [10] and the experimental verification and difficulties of V2G are expressed in [11]. The contactless charger suitable for Indian Power Grid environment and benefits are projected in [12] and requirements of bidirectional charger for V2G is discussed in [13]. The new approach to V2G connection is proposed in [14] and economic opportunities related to V2G aspect is presented in [15].

After reviewing the available literature, we found that there are only few papers which discuss specifically about the On-Board and Off-Board V2G integration techniques. The integrators play a critical role in effective and efficient use of V2G. The modeling of the Off-Board integrator is proposed and simulation is carried out using MATLAB/SIMULINK. The efficiency of power conversion and the architectural benefits are discussed. The Off-Board integrators are preferred in charging stations and have to comply with IEEE 1547 standard.

3. Modeling of V2G

The EVs can be connected to the grid through household or other interface and has impact on household or grid. An accurate EV model improves the control strategy for household or grid. The equations below describe the power flow of EVs when they are connected to the grid [4].The EVs can be connected to the home grid and this is known as Vehicle-to-Home (V2H). The mathematical model of V2H is given by:

$$P_t^L + \sum_{n=1}^{N} P_{t,n}^{EV} \le P_{t,\max}^{H}, t = 1 \sim \mathrm{T} \qquad (1)$$

where,

P_t^L is the power of domestic electrical loads at the t^th^ time period

$P_{t,n}^{EV}$ is the output power of the n^th^ EV at the t^th^ time period

$P_{t,\max}^{H}$ is the maximum power of the entire home at the t^th^ time period

T is the number of time period

The EVs can be connected to the other EVs and is known as Vehicle-to-Vehicle (V2V) for the charging and is given in equation (2).

$$\sum_{n=1}^{K} \eta_n^{EV} P_{t,n}^{EV} = 0, t = 1 \sim \mathrm{T} \qquad (2)$$

where,

η_n^{EV} is the efficiency of the nth charger

$P_{t,n}^{EV}$ is the output power of the nth EV at the t^th^ time period

A large number of EVs can be connected to the grid for power transaction and is called as Vehicle-to-Grid (V2G). The basic constraints for the V2G model can be summarized as:

$$P_t^L + \sum_{n=1}^{N+K} \eta_n^{EV} P_{t,n}^{EV} = P_t^{PS}, t = 1 \sim \mathrm{T}$$

$$t = T_n^c \sim \mathrm{T}_n^d, n = 1 \sim \mathrm{N+K} \qquad (3)$$

where,

T_n^c is the number of the time period when the n^th^ EV is connected to the home grid

T_n^d is the number of the time period when the n^th^ EV is disconnected from the home grid

N is the number of EVs at home

K is the number of EVs in aggregation

The constraints for the V2G are listed below in the equations (4) to (10).

The available capacity (controllable power) is given by:

$$|\,\mathrm{P}_{t,n}^{EV}\,| \le P_{n,\max}^{EV} \quad t = T_n^c \sim \mathrm{T}_n^d, n = 1 \sim \mathrm{N+K} \qquad (4)$$

where,
$P_{n,\max}^{EV}$ is the maximum power of the nth EV at the t^th^ time

The SOC limitations are given by:

$$\mathrm{SOC}_{n,\min} \le SOC_{t,n} \le SOC_{n,\max}$$
$$t = T_n^c \sim \mathrm{T}_n^d, n = 1 \sim \mathrm{N+K} \quad (5)$$

where,
$SOC_{\mathrm{n,min}}$ is the minimum value of the SOC of the nth EV
$SOC_{t,n}$ is the state of the charge of nth EV at tth time period
$SOC_{\mathrm{n,max}}$ is the maximum value of the SOC of the nth EV

The driver choices:

$$\underset{t=T_n^c-T_n^d,\, n=1\sim\mathrm{N+K}}{\mu_{t,n}} = \begin{cases} 1, \; P_{t,n}^{EV} \ge 0 \\ -1, \; P_{t,n}^{EV} \le 0 \end{cases} \quad (6)$$

where,
$\mu_{t,n}$ is the sign of the charging/discharging operation

The arrival and departure time of:

$$\underset{t=T_n^c-T_n^d,\, n=1\sim\mathrm{N+K}}{\eta_n^{EV}} = \begin{cases} \eta_n^{GC}, \; \mathrm{P}_{t,n}^{EV} \ge 0 \\ \eta_n^{GD}, \; \mathrm{P}_{t,n}^{EV} \le 0 \end{cases} \quad (7)$$

where,
η_n^{GC} is the charging efficiency of the nth charger
η_n^{GD} is the discharging efficiency of the nth charger

$$\underbrace{SOC_{t,n}}_{n=1\sim\mathrm{N+K}} = \begin{cases} \dfrac{W_n^c + P_{t,n}^{EV}\eta_n^{EV}\Delta T}{C_n}, \quad t = T_n^c \\ SOC_{t-1,n} + \dfrac{P_{t,n}^{EV}\eta_n^{EV}\Delta T}{C_n}, \\ t = T_n^c + 1, ...T_n^d \end{cases} \quad (8)$$

where,
W_n^c is the is the initial capacity when EV is connected to the home grid
ΔT is the length of the time period

$$\sum_{t=T_n^c}^{T_n^c}\left[P_{t,n}^{EV}\eta_n^{EV}\Delta T\right] = W_n^d - W_n^c, \; n = 1 \sim \mathrm{N+K} \quad (9)$$

where,
W_n^d is the resulted capacity when EV is disconnected from the home grid

The charger capacitor is given by:

$$q \le \sqrt{s^2 - p^2} = q^{\max} \quad (10)$$

4. Off-Board V2G Integrator Framework

The Off-Board V2G integrator is altogether a different approach when compared to the On-Board types. The Off-Board V2G integrator facilitates multiple EVs to be connected to the grid. The parking areas of any company or institution can play a major role in supporting grid and can get the major economic benefits. The block diagram of the Off-Board integrator is shown in Fig.1. The battery charger play a prominent role in the development of EVs and charging/discharging time of the battery are linked to the characteristics of the battery charger. The operation of chargers depends on components, control and switching strategies. The EV charger must draw the utility current with low distortion to minimize impacts of power quality and maximize the real power available from a utility outlet at high power factor. The EV battery charger contains a boost converter for power factor correction (PFC) and uses a dedicated diode bridge to rectify the ac input voltage to dc. With the use of multilevel converters avoids a low frequency transformer and in turn reduces the size, switching frequency, and stress of the devices. It also provides high power factor and reduced THD of current at the input. The battery chargers are classified in to two categories: on-board and off-board and support both unidirectional and bidirectional power flow. Unidirectional charging limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation. A bidirectional charging system supports charge from the grid, battery energy injection back to the grid, and power stabilization with adequate power conversion.

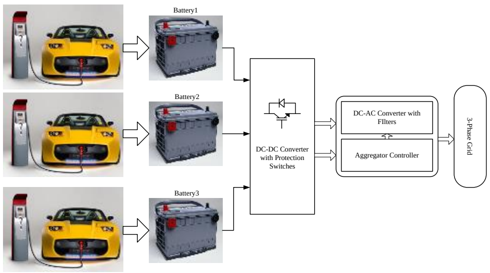

Fig. 1. Block diagram of Off-Board integrator.

2.1. *Modelling of Controller for Grid side Inverter*

The inverter is of typical three phase six switch pulse width modulation (PWM) voltage source inverter. The VSI converts the power from the DC voltage source to three phase AC outputs with 120° phase displacement. PWM is modulation technique used to control and shape the VSI output voltage. In order to control the magnitude, phase angle and frequency of the output voltage of VSI, PWM is used to generate switching pulses to control the six switches in VSI. In PWM three balanced sinusoidal control voltages are compared with the triangular voltages. The triangular waveform is at a switching frequency, which is generally much higher than the frequency of the control voltages and is called as carrier frequency. The three phase sinusoidal control signals with the same frequency are used to modulate the duty ratios of switching pulses from the switches. The active power flow is controlled by varying the phase difference and reactive power flow is by varying the magnitude of inverter output. The phase difference and amplitude are varied with reference of constant grid voltage.

The active and reactive power control scheme (PQ control) is used when the inverter is operated to meet grid connected operation and active power and voltage scheme (PV control) is used when the inverter is operated to meet isolated operation. PQ control scheme of VSI is shown in Fig. 2.

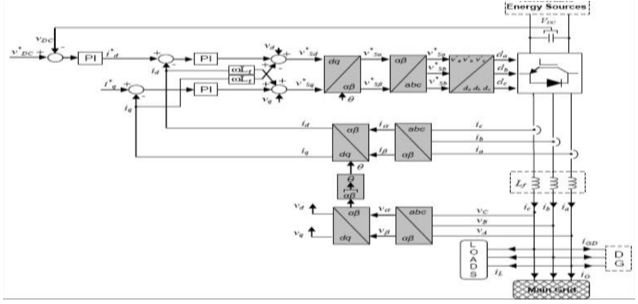

Fig. 2. Inverter controller block diagram in grid connected mode of operation.

The inverter is used for the connecting EV to the grid. Therefore a PI controller is used to keep the output current sinusoidal and to have high dynamic performance for different conditions [16]. The PI algorithm is used for feedback controller and is shown in Fig.3. The current injected into the grid I_g is sensed and fed back to a comparator which compares it with the reference current I_{ref}. I_{ref} is obtained by measuring the grid voltage and multiplying it with variable m. Here m is a modulation index to generate I_{ref}.

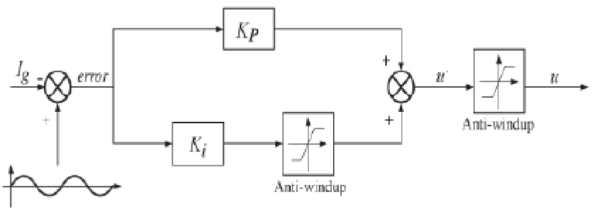

Fig.3. PI control algorithm.

The PI algorithm can be expressed in the continuous time domain as:

$$u(t) = K_p e(t) + K_i \int_{\tau=0}^{t} e(\tau) d(\tau) \qquad (11)$$

where, error e(t) is set point output, K_p is proportional gain and K_i is the integral gain.

5. Simulation Results

Two EV batteries with fairly different discharging characteristics are connected in series for supplying power to the grid. Here we need a buck converter for reducing voltage level due to series connection and the specifications used for simulation are shown in Table 1. It is observed that the proposed model has constant DC link voltage and a purely sinusoidal controlled ideal voltage source at the inverter terminals. The output voltage of the buck converter settles at 400V as shown in Fig.4 and connecting it to the grid we need the inverter. The output voltage of the inverter is shown in Fig.5. The inverter output current is shown in Fig.6 and in the Fig.7 load line voltage and line current are plotted together to note the phase difference between the two. The Fig.7 depicts that there is no much phase difference and satisfies the resistive nature of the load. The power drawn from the battery and the grid are shown in comparison to load power are shown in Fig8. The frequency variation is shown in Fig.9.

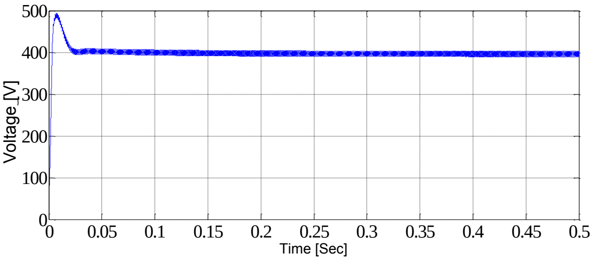

Fig.4. Buck converter output with filter.

Table 1. Specifications for two EV's connected to the grid

Battery Specifications	Buck Converter	Grid and Load Specifications
V_{batt} = 400 V	Duty ratio=35%	V_{grid}=415V, f=50Hz
I*h =62.5 Amp hour	Switching frequency=1kHz	Load=100kW, Resistive at V_L=415V
Battery Energy Capacity=24kWh	Ls=0.5µH, Cs=2µF	L=0.9mH,C=110µF

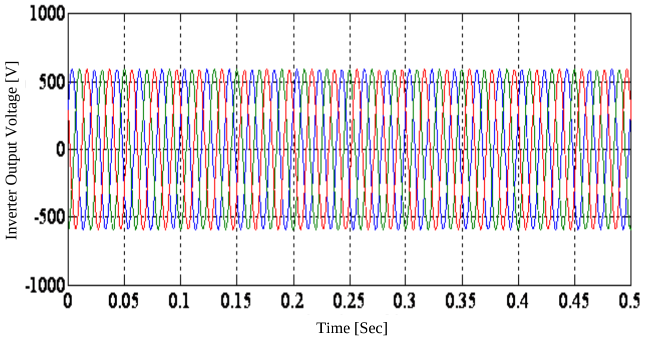

Fig.5. Inverter output voltage.

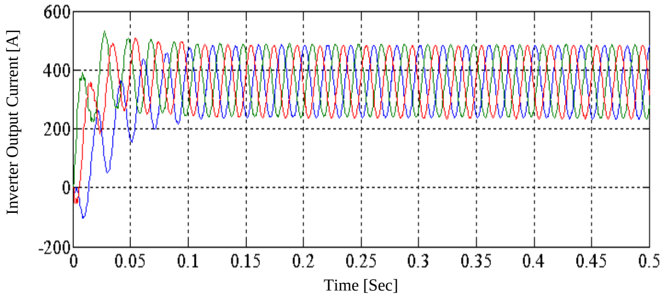

Fig.6. Inverter output current.

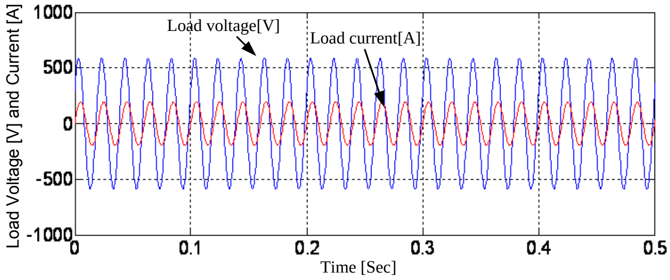

Fig.7. Load voltage and current.

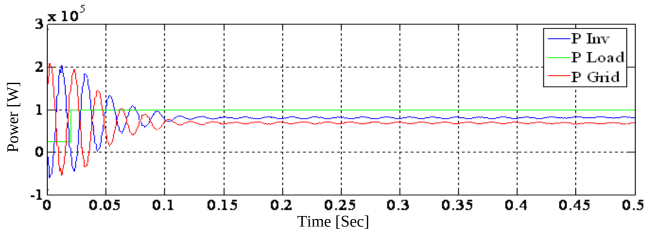

Fig.8. Grid, inverter and load power waveforms

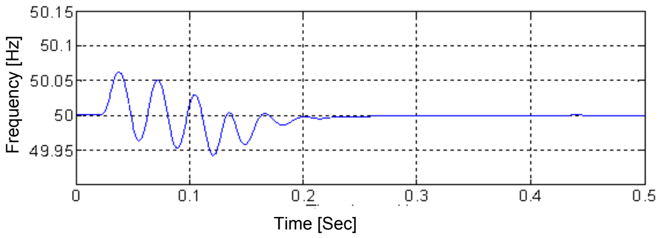

Fig.9. Grid frequency.

6. Conclusion

The Off-Board V2G integrator is modeled using MATLAB/SIMULINK and the V2G operation (discharging) is considered with two vehicles being connected to the grid. The developed V2G integrator model facilitates EVs to get connected to the grid. The simulation results demonstrate that the Off-Board Integrator has the conversion efficiency of around 91.85% and is better suitable for V2G operation. The Off-Board integrator is common to all the EVs and complies with IEEE 1547 standards. The model serves as a base for modelling V2G Integrators for power transaction when EV is connected to the grid.

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