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ORIGINAL PAPER

Techno-Economic Evaluation of Regulation Service from SEVs in Smart MG System

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Abstract A techno-economic evaluation of regulation service of microgrid system comprising renewable energy resources and electric vehicles has been done in this paper. EV operational strategy for MG regulation is developed by incorporating a vehicle controller which enables vehicle to grid or grid to vehicle mode operation, while plugged into the power distribution circuit. The functionality of grid integration of electric vehicle with vehicle to grid or grid to vehicle operation makes it a smart electric vehicle, suitable for operation in smart microgrid environment. The techno-economic analysis is based on simulation results obtained from a microgrid test system operated with varying power generation and frequency regulation being provided by two different microgrid resources i.e., conventional battery storage system and proposed smart electric vehicles. The cost for providing frequency regulation using battery storage system and grid integration of vehicle is calculated and compared to find microgrid optimal operation option. The comparison of two costs reveals that smart electric vehicles have considerable economic potential for microgrid regulation service and hence provide better utilization of resources for optimal operation.

Keywords Battery storage system · Capacity cost · Cost of regulation-up · Energy cost · Smart electric vehicle · Regulation services and vehicle to grid mode

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Introduction

ELECTRIC power system has been undergoing evolutionary changes in response to the stringent requirements of power quality, reliability, improved operational efficiency, environmental compliance and energy conservation. Recent focus of power industries is to develop smart grids for improved power distribution system and also to upgrade conventional grids with smart grid technologies. A smart grid may be defined as the electrical power system with advanced electrical infrastructure, intelligent communication and control network integrated with smart electrical appliances and smart electric vehicles (SEVs) [1, 2]. Micro-grids (MGs) are proving to be more promising, operating at low voltage, with distributed energy resources (DERs), storage devices and local loads to commensurate these profound changes [3, 4]. Microgrid is a localized grouping of electric power resources and loads that normally operate connected and synchronized with the traditional centralized grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate. More simply microgrid can be defined as a subset of macrogrid. A number of recent research work related to design, control and operation [5–7] of microgrids can be found in literature however attention towards the economic issues associated to the microgrid design and operation is less. Microgrid generally comprises of renewable power generation like solar photovoltaic (PV) generator or wind turbine but their power output is intermittent owing to the dependence on natural factors like irradiance and wind speed due to which these generators generally require storage batteries to maintain power balance between generation and load demand. Batteries also play important role in frequency regulation due to their quick response and two-way power transfer capability [8, 9]. Non-renewable resources in a microgrid may comprise of diesel generators or micro gas turbines. The operation and maintenance cost of these distributed energy resources alongwith expensive battery storage systems (BSS) increases the overall operational cost of microgrid. Som et al. [10] suggest that electricity cost per unit in microgrid system comprising biomass gassifier, solar photovoltaic generator and battery storage system and for microgrid system with fuel cell generator, solar photovoltaic generator and battery storage system comes out to be US$ 0.278 and US$ 0.304 respectively. The electricity generation within microgrid has several advantages like reliability, no-transmission losses, less carbon emissions, etc. but cost per unit is higher as compared to the main grid. Thus there is a need to device techniques to make microgrid operation economical, to enhance the benefits. Seon-Ju Ahn et al. [11] presented an optimization technique to minimize the fuel cost from grid connected operation to islanding of a microgrid system. An economic dispatch problem is solved using direct search method with constraints formulated for fixed-droop and adjustable droop principle. Their method provided a precise solution for economic dispatch in conventional microgrid system. The work presented in our paper is related to the economics of advanced smart MG systems which involve smart electric vehicles.

In recent years there have been major improvements in electric vehicle technologies and increase in their deployment in mass market. Majority of the previous work regarding grid integration of electric vehicle focuses on their coordinated charging technologies for energy management and optimised operation [12–14]. Evaluation of widespread use of electric vehicle in a smart grid by analyzing adequacy indices and security perspective is done in [15], leading to the results that the managed charging and vehicle to grid scenarios can be used to improve the smart grid operation. This is due to the reason that electric vehicles act as storage system while not in movement. Hence it will be interesting to propose the grid integration of vehicle for further smart grid services like regulation service as presented in our paper here.

Work has also been done to analyse the impact of electric vehicle integration on distribution circuits [16–18]. Technical description and comparison of centralised and decentralised grid integration of vehicle (GIV) mechanisms for providing regulation service is described and compared in [19]. For centralised GIV mechanism, quadratic optimization problem is solved to find the individual regulation power and preferred operation point (POP). Decentralised GIV mechanism is agent-based system in which electric vehicle agent autonomously calculates its regulation power using POP calculation method. Authors in [20] showed that microgrid system performance improved considerably when electric vehicles were used to help in frequency control and also that a large number of electric vehicles can be integrated while adopting advanced centralized electric vehicle charging control strategies without the need to proceed for grid reinforcement. Practical demonstration of vehicle to grid power providing real-time frequency regulation from electric car is reported in [21]. While the literature review showed that the analysis on grid integration of electric vehicle is quite extensive, there is still a need to analyse its impact with respect to microgrid paradigm.

Microgrid systems do not have conventional automatic generation control and spinning reserves, thus the task of providing regulation services for a microgrid becomes more challenging. Battery storage system provides a technical solution for primary as well as secondary frequency regulation of microgrid however their high capital and maintenance cost is an important issue [22]. The objective of this paper is to develop the concept of grid integration of vehicle for microgrid support. Analysis is done to check the techno-economic viability of electric vehicle integration to enhance the microgrid operational efficiency. In this work smart electric vehicles are used to provide frequency regulation in place of battery storage system in a smart microgrid. The economic value of regulation service using vehicle to grid/ grid to vehicle (V2G/G2V) operation of smart electric vehicles is compared with regulation provided by battery storage system.

Regulation Service Using SEVs

For an electric power system, ancillary services are important to maintain reliability of the grid while providing separate markets for electric power sale and purchase. These are also important to commensurate with the load variations of the power distribution system. In a MG system we are more concerned with regulation ancillary services. Regulation may be defined as the automatic generation control of online power resources that can respond rapidly to system-operator requests to correct for unintended fluctuations in the power distribution system so as to comply with Control Performance Standards (CPSs). The main purpose of regulation here is to control the MG frequency and voltage to the reference levels [23]. In a MG, primary as well as secondary frequency regulation is provided by battery storage system and/or load shedding or demand response techniques (in SMGs). Large EV penetration in a MG system as a dumb load may cause higher peak demand, feeder congestion or undue overloading of the transformers leading to unbalance situations. An electric vehicle control strategy is designed and proposed here to enable electric vehicle to provide regulation-up (V2G) and regulation-down (G2V) service in response to the MG transient situations. Electric vehicle equipped with this controller will operate as a 'smart electric vehicle'.

The electricity from grid integration of vehicle (GIV) is costly when compared to electricity from large power plants but it can provide ancillary services like peak load shaving, regulation services, spinning reserves, etc in a power distribution market. National household travel survey [24] suggests that EVs are parked for more than 90 % of the time. For this reason the fleets of EV can become a potential source of power to the microgrid without compromising on their driving schedule. Figure 1 represents the basic architecture of a MG system with smart electric vehicle, renewable (PV generator and wind turbine) and non-renewable (single shaft microturbine, SSMT) resources. There is a MG central controller (MGCC) responsible for microgrid control and power balance. Smart electric vehicle controller (SEV C) checks and controls the EV operation while plugged into the distribution circuit.

Smart Electric Vehicle Operation

SEVs incorporate a vehicle controller which operates in dual-mode i.e., V2G and G2V mode. In the former operation mode, SEV injects electric power to the grid and in the latter operation it consumes electric power from the grid to charge its battery. The charging/discharging control can be performed through power- frequency droop control strategy as shown in Fig. 2. The droop constants can be fixed or adjustable. According to adjustable droop principle the droop constants are periodically modified with respect to the operating points of the distributed generator, which in this case is an active load (SEV). With this technique DG shares power according to their operational reserves, however in fixed droop control the droop constants are fixed parameters and the load demand is shared among DGs in proportion to their capacities. In this work fixed droop principle is adopted with the inclusion of battery state of charge (SOC) in it. A phase-locked loop is used to measure frequency deviations at each EV grid interface. The dead-band and slope of the frequency droop determines the operational parameters of EV and may be decided by the vehicle owner or MG operator depending upon the MG frequency regulation system requirement. The controller initiates charging (G2V mode) or discharging (V2G mode) actions whenever the frequency deviation is more than the frequency dead band and the slope of the frequency droop characteristic

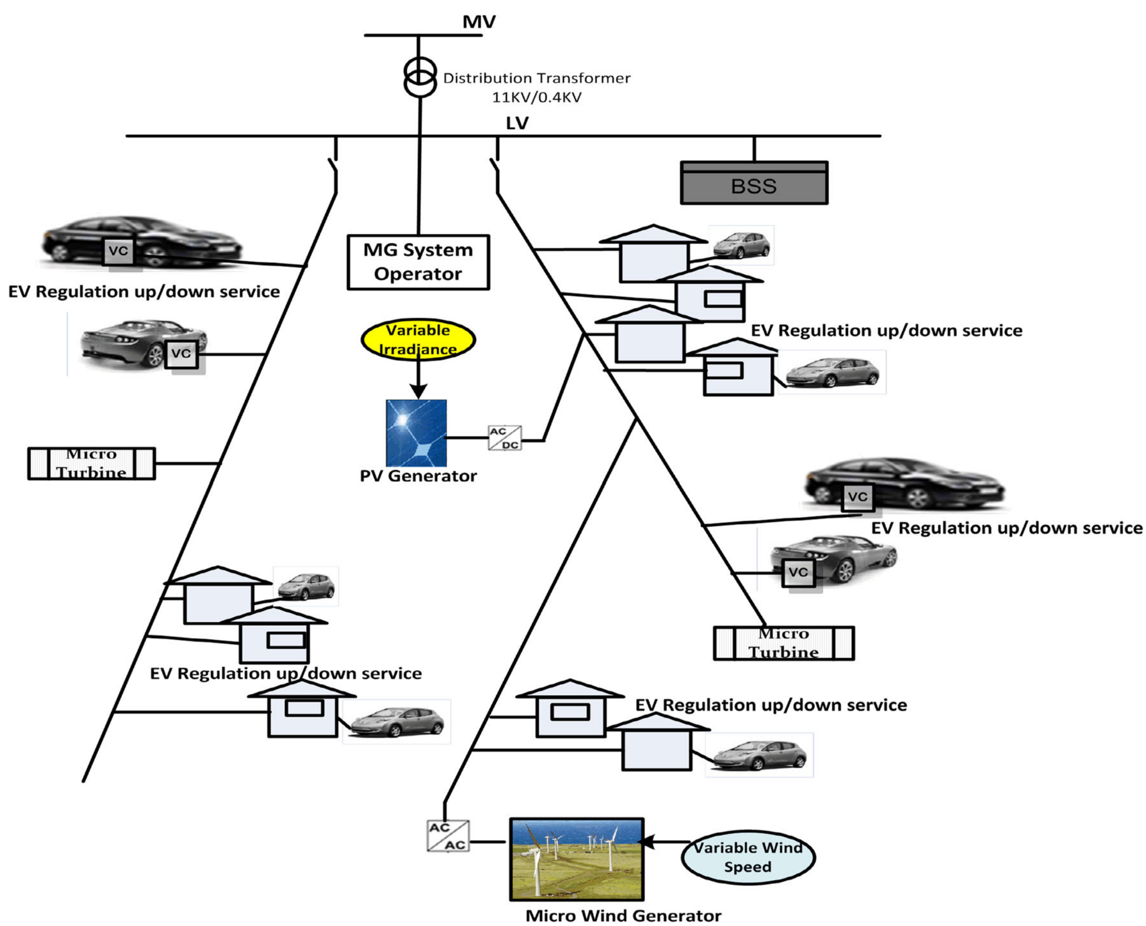

Fig. 1 MG System with BSS and SEVs

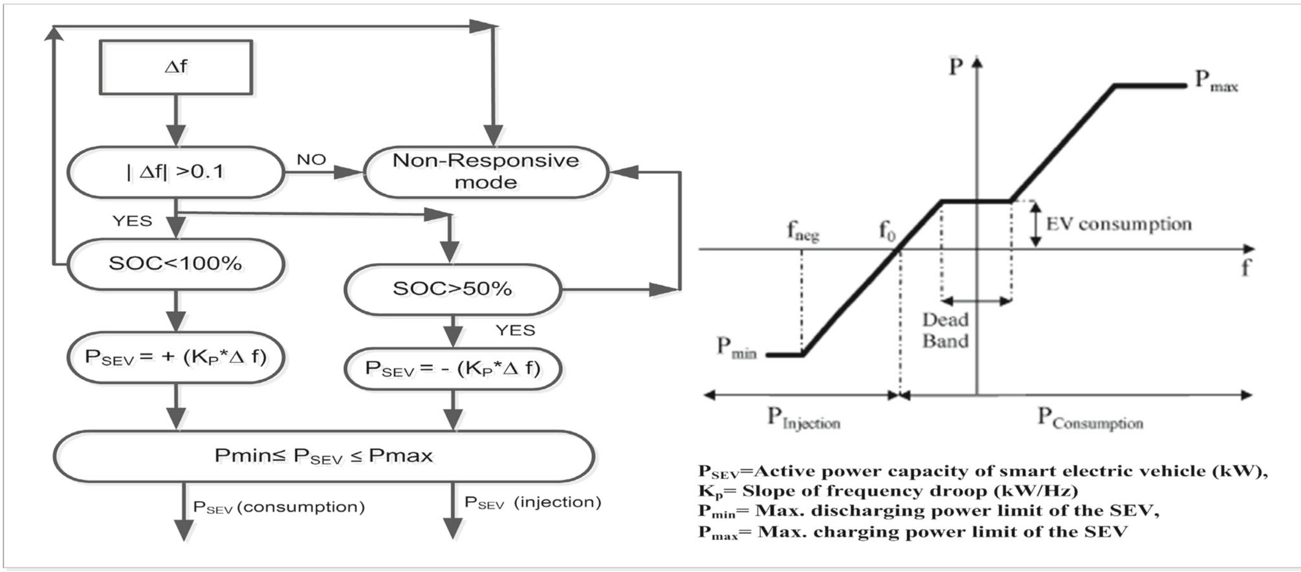

Fig. 2 Smart Electric Vehicle Controller with p-f droop

decides the rate of charging and discharging of vehicle. In case of generation shortfall or high power demand, frequency of the system drops below the reference level. As soon as the frequency deviation crosses vehicle controller lower set point, vehicles with state of charge higher than 50 % participate in power injection (V2G mode). This provides frequency regulation-up service. In case of excessive power generation or low power demand in the MG, frequency increase above the specified levels of vehicle controller and SEVs with SOC less than 100 % move in G2V mode where controller initiates charging action and regulation-down service is aided.

Proposed Frequency Regulation of MG with SEV

MG generation and load demand unbalance cause frequency deviations and requires regulation service to restore stability and autonomous operation. MG frequency control strategy shown in Fig. 3 can provide adequate framework to exploit the EV controllability in smart MG environment. Vehicle controller is integrated to form a frequency control loop. Disturbances in MV network, sudden changes in the MG non-controllable resources (due to sudden change in wind speed and irradiance level) or sudden change in the amount of load connected to the MG result in frequency deviation, Δf and power imbalance ΔP, as shown in Eq. 1.

$$\Delta P = P_{SSMT} + P_{PV} + P_{WT} \pm P_{SEV} \pm P_{grid} - P_L \quad (1)$$

P_{SSMT} is the power output of SSMTs, P_{PV} is the power output of solar generator, P_{WT} is the power output of micro wind generator, P_{grid} is the power import or export with the main grid and P_L is the load connected to the MG. Energy imbalance of the MG, for a specified period of time is denoted by E. T_{dP} is the time delay due to response of voltage source inverter and T_{inv} is the time delay of SEV grid interface inverter. ΔP gives rise to frequency deviation Δf and for this kind of situation emergency regulation action of SEV is initiated through vehicle controllers to provide frequency regulation for the MG transient situation.

Cost Calculation for MG Regulation Service

The economic potential of regulation service with the EV depends critically on the cost, MG utility owner is required to pay for regulation up and regulation down power to the vehicle owner. Electric vehicle is privately owned resource, therefore MG utility purchases the regulation power from EV owners and the payments are made on the basis of regulation contract, which is comprised of two components (i) contract payment of availability and (ii) energy payment per kWh when power is supplied. The charges for providing regulation up and down may be different or same. Equations 2–4 give the revenue paid by the utility to EV owner for providing regulation up and regulation down service respectively. For a particular MG situation total cost for regulation-up will depend upon the contract to dispatch ratio.

$$R_{reg-up} = P_{cap} H_{disp} P_{veh} + P_{el} H_{disp} P_{veh} R_{d-c} \quad (2)$$

$$R_{reg-down} = P_{cap} H_{disp} P_{veh} \quad (3)$$

$$R_{d-c} = \frac{E_{disp}}{P_{veh} H_{disp}} \quad (4)$$

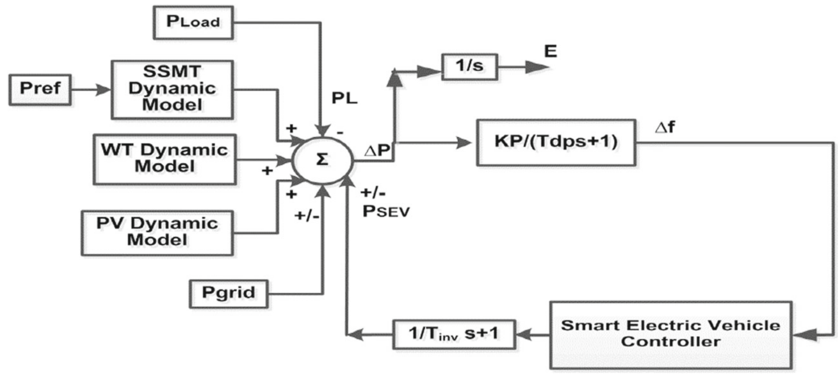

Fig. 3 MG Frequency Regulation scheme using SEV

Here, P_{cap} = capacity price, P_{el} = market selling price of electricity, P_{veh} = vehicle power, R_{d-c} = dispatch to contract ratio, and E_{disp} = energy dispatched, H_{disp} = number of hours vehicle is plugged in for regulation. The cost incurred for providing regulation by BSS comprises of cost of energy supplied/consumed for battery replenishment in real time and annualized capital cost of the BSS including the capital recovery factor. Equations 5–9 are formulated to calculate this cost.

$$C_{BSS} = C_{en} P_{conv} H_{ch} + C_{ac} \tag{5}$$

$$C_{en} = \frac{C_{pe}}{\eta_{conv}} + C_D \tag{6}$$

$$C_D = \frac{C_{bat}}{L_{bat}} = \frac{E_S C_B + C_1 t_1}{L_S E_S DoD} \tag{7}$$

$$C_{ac} = C_C * CRF \tag{8}$$

$$CRF = \frac{d}{1-(1+d)^{-n}} \tag{9}$$

C_{en} =cost per energy unit including losses and battery degradation, P_{conv} = capacity of the converter, H_{ch} = total number of hours taken for charging/energy dispatch, C_{pe} =cost of electricity for recharging in distribution market, η_{conv} =converter efficiency, C_{bat} = battery replacement cost (capital & labor), L_{bat} = battery lifetime energy throughput for a particular cycling regime, E_S = total energy storage of the battery, C_1 = cost of labor, t_1 = labor time for battery replacement, L_s = battery lifetime in cycles, CRF= capital recovery factor, d = discount rate, n = number of years during which investment of BSS is amortized and C_{ac} = annualized capital cost of BSS. The mathematical equations formulated above can be used to find the economic value involved in providing frequency regulation using smart electric vehicles (Eqs. 2–4) and battery storage system (Eqs. 5–9) for a microgrid.

Simulation Results and Evaluation of Regulation Services

To access the viability of V2G power for grid support, different scenarios with microgrid generation variations are simulated in a test network. A residential distribution circuit is designed and simulated in MATLAB Simulink as the case study platform [25]. It is a 500kVA, 11/0.433kV LV microgrid system, Fig. 4, which can operate autonomously as well as connected to the grid. The network has four radial feeders with distributed generators like solar photovoltaic (PV) generator, a micro-wind generator and two single shaft micro turbines. Microgrid central controller (MGCC) monitors and controls the MG stability. Most of the loads operating in the MG are household loads. The loads also comprise of electric vehicles which connect to the network throughout single phase chargers for charging purpose as well as to provide power injection and regulation service. An average number of vehicles in Indian urban household is 1.3 [26], therefore for 96 houses present in the microgrid a fleet of 125 vehicles, charging at recommended rate, is considered in this study. The description of the electric vehicle considered is presented in Table 1.

The MG test system also has a battery storage system, the capacity of which is varied from 50kVA to 300kVA to simulate different MG situations and therefore the converter power for every simulation is different. MG is operated with 271kW of average load. The total generation from different sources of MG is varied from 50kW-500kW to analyze the effectiveness of SEVs operation for microgrid frequency regulation.

Results and Technical Analysis

Frequency regulation is provided separately using the BSS and then GIV. The simulation results presented in Fig. 5a shows that frequency regulation is provided by BSS when frequency deviation of more than 0.9Hz is seen for excessive decrease in MG generation. The results for regulation service by BSS for average increase in MG generation from

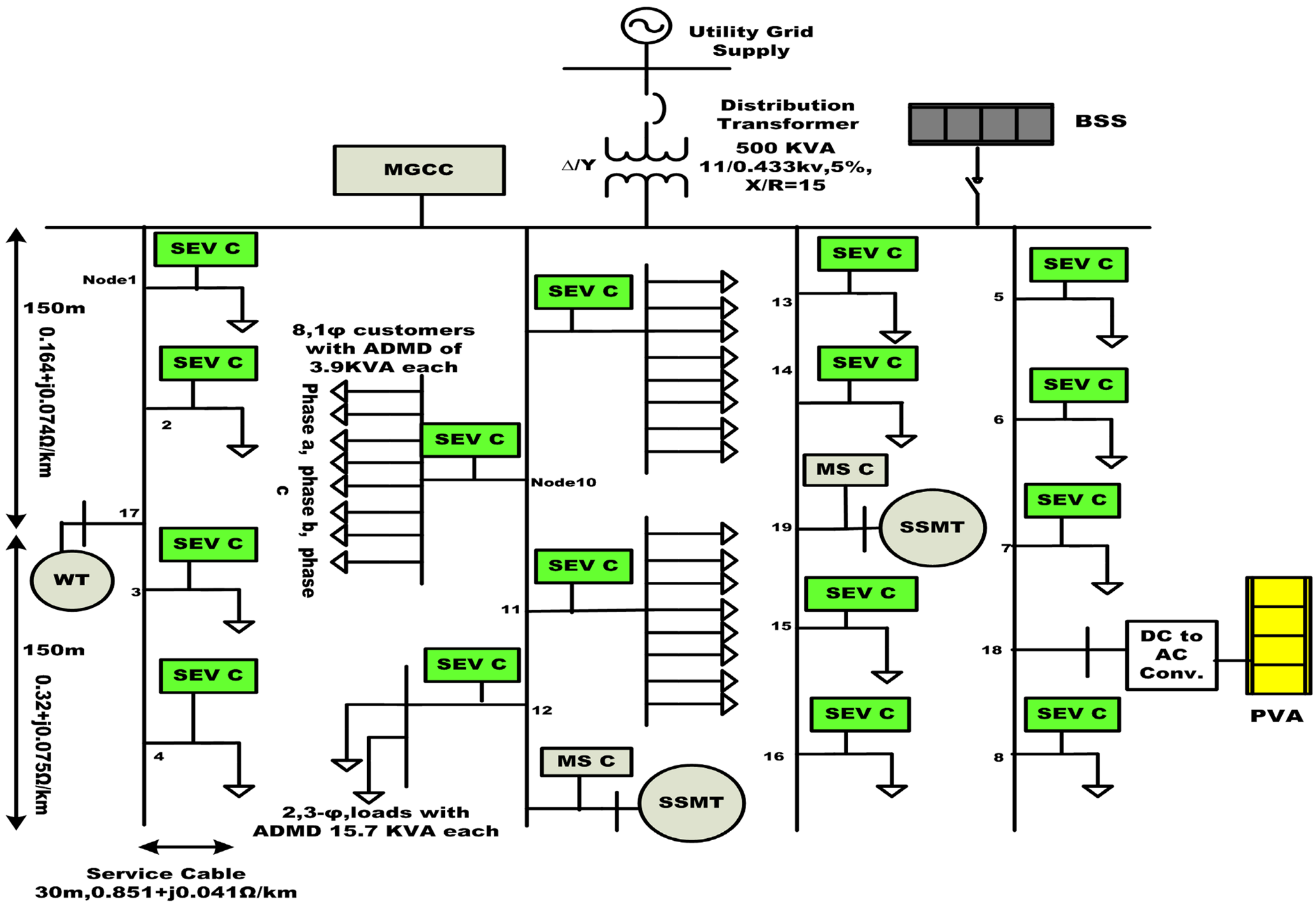

Fig. 4 MG Test System

271kW to 310kW are shown in Fig. 5b. Figure 6 illustrates the frequency regulation of MG with SEVs. In case of sudden decrease in MG generation from 271kW to 50kW, Fig. 6a, frequency stabilizes from 49.5Hz to 50Hz when regulation is provided by GIV. For this situation, 54.4 % of SEVs move into V2G mode for providing MG frequency regulation with 40 % SEVs which were initially in G2V mode either went into non-responsive mode or V2G mode depending upon their SOC. However in 6b, with increase in MG generation from 271kW to 350kW, 19.2 % SEVs adopt G2V mode to provide frequency regulation. Results for different MG situations are tabulated in Table II, to carry out the economic analysis. It can be seen that in scenarios 1-5, power generation of the MG is less than the average load of the system hence frequency deviates below the reference level contrary to scenarios 6-10 which results in frequency deviation above the reference level. For frequency regulation using BSS, the BSS capacity is changed between 50kVA to 300kVA for regulation-up or regulation-down until the frequency reaches the reference value. For different MG situations different levels of GIV helps in stabilizing MG frequency by operating in V2G or G2V mode. As shown in Table 2, GIV may change from 54.4 % to 7.3 % to provide frequency regulation in a MG with average load of 271kW and varying generation. It can also be observed from the simulation results that although the regulation with BSS is faster as compared to GIV but it has higher frequency fluctuations and the frequency regulation with GIV is smooth and seamless. This is because of the reason that SEVs are equipped with more advanced and sensitive controller.

Results and Economic Analysis

The cost of BSS regulation service is calculated using Eqs. 5–9. The battery cost has two components i.e., energy

Table 1 EV Specifications

EV	Battery size	Energy available	All Electric range	Charger Power
Nissan LEAF	24kWh	19.2KWh	100 mi, LA4 mode	3.3kW (recommended)

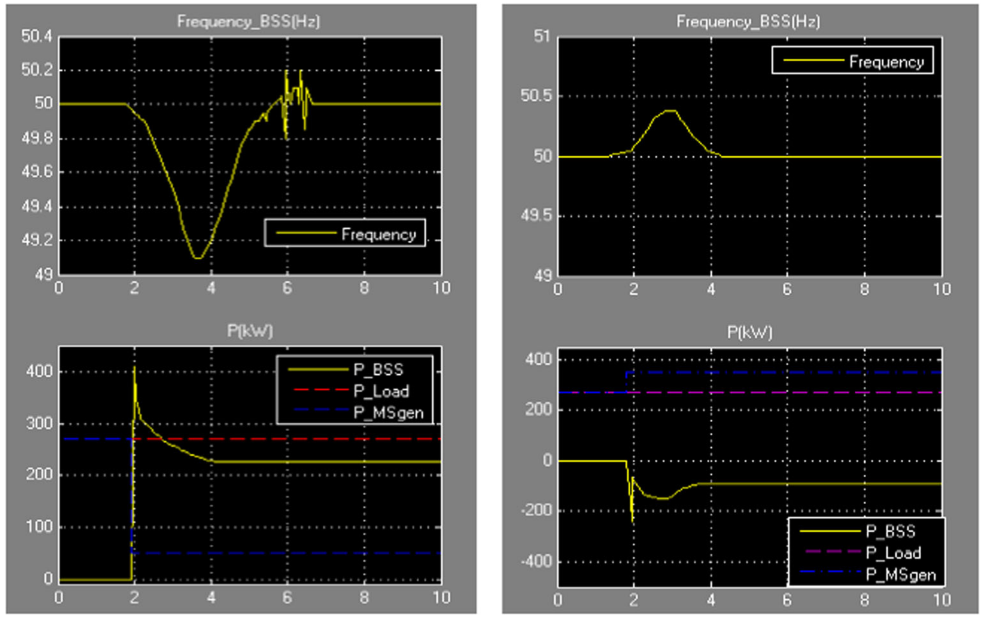

Fig. 5 Frequency Regulation with BSS, (**a**) excessive decrease in MG Power Generation (**b**) average increase in MG Power Generation

cost component and capital cost component. The capital cost of battery is annualized for the discount rate of 10 % and the investment is assumed to be amortized for a period of 10 years. The battery degradation, maintenance and replacement costs are also included in total cost calculation. For regulation service, cycling regime will be most of the time shallow type, therefore battery degradation cost here will be lower. Cost of regulation with SEVs is calculated using Eqs. 2–4. This cost is actually the revenue which MG utility has to pay to the SEV owners involved in regulation service. It includes the capacity price paid for the energy available for frequency regulation service and price paid for the unit supplied in real time. There is a MG system operator responsible for power exchange agreements. The dispatch to contract ratio, R_{d-c} for GIV is taken here as 0.9, considering that the participant adheres to contract terms. The capacity price is assumed to be fixed at \$0.004/kWh^{-1} and for different MG scenarios considered

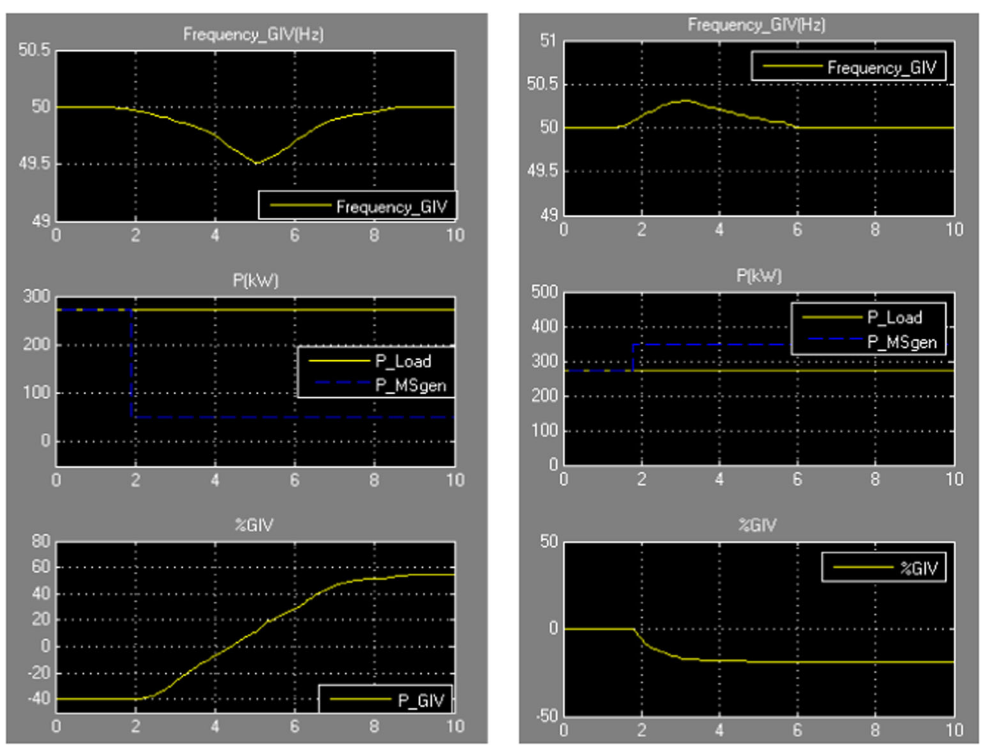

Fig. 6 Frequency Regulation with GIV, (**a**) excessive decrease in MG Power Generation (**b**) average increase in MG Power Generation

Table 2 Simulation Results for Frequency Regulation under different MG Generation Levels

Scenarios	Average MG Generation (kW)	BSS Capacity (kVA)	GIV (%)	Regulation Service Type
	50	300	54.4	Regulation-up
2	100	240	43.2	
3	150	180	31.2	
4	200	120	19.2	
5	250	50	7.3	
6	300	50	7.3	Regulation-down
7	350	120	19.2	
8	400	180	31.2	
9	450	240	43.2	
10	500	300	54.4	

Table 3 Distribution System Regulation Price

Year	Regulation Price (Rs/KWh)	Regulation Price (US $/KWh)
2008–09	6.70	0.101
2009–10	4.62	0.069
2010–11	3.91	0.059
2011–12	4.09	0.062
2012–13	3.86	0.058
2013–14	2.05	0.031

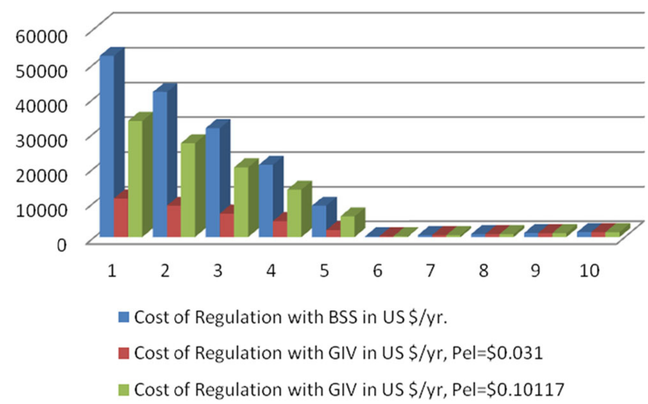

Fig. 7 Comparison of the Cost of Regulation with BSS and GIV for different MG Scenarios

in this study, 4 hours of dispatch time is observed. The regulation prices for consecutive six years are obtained from ISO [27] and represented in Table 3. The analysis is done for Indian system but for the convenience of international readers, the cost figures are approximated to US dollars at the rate of Rs 66.21/US $. The cost of regulation with GIV is calculated with minimum and maximum regulation prices of the system. Results obtained after calculating cost/year of regulation using BSS and GIV are presented in Table 4. The values of different constants used for economic analysis are presented in Table 5 at appendix. The results reveal that in a MG system, GIV for frequency regulation is cost effective. It is observed that for different scenarios of MG generation and load imbalance, GIV provides the average annual saving of more than 75 % & 30 % for higher regulation price & lower regulation price respectively as

Table 4 Comparison of Regulation Service cost using BSS and GIV with minimum and maximum Regulation Price

Scenarios	Cost of Regulation with BSS in US $/yr.	Cost of Regulation with GIV in US $/yr Pel=$0.031	Savings with lowest regulation price	Cost of Regulation with GIV in US $/yr Pel=$0.10117	Savings with highest regulation price	Type of Regulation Service
1	52,243.58	11,219.68	78.52 %	33,431.47	36.01 %	Regulation-Up
2	41,794.87	9,067.96	78.30 %	27,019.96	35.35 %	
3	31,346.15	6,762.54	78.43 %	20,150.48	35.72 %	
4	20,897.43	4,610.83	77.94 %	13,738.96	34.26 %	
5	9,045.50	1,998.02	77.91 %	5,953.55	34.18 %	
6	241.6	231.264	4.28 %	231.264	4.28 %	Regulation-Down
7	579.84	578.16	0.29 %	578.16	0.29 %	
8	869.76	847.968	2.51 %	847.968	2.51 %	
9	1,159.68	1,137.05	1.95 %	1,137.05	1.95 %	
10	1,449.60	1,406.86	2.95 %	1,406.86	2.95 %	

compared to BSS for providing same volume of regulation-up service to the MG system, Fig. 7. For regulation down service savings are not significant because it involves the capacity cost factor only. The revenue paid per year to individual owner is $19.2 for regulation down, $153.69 (with lower regulation price) and $457.97 (with higher regulation price) for regulation up participation. Overall results favours GIV and it is found that not only technically but economically also GIV ensures a good replacement of costly BSS in providing regulation services for the MG system.

Conclusion

An analysis has been done to evaluate the use of electric vehicles for providing regulation in a microgrid system with intermittent power generation from distributed resources (PV array and wind turbine). Regulation service is of short duration but involves high value power market. Conventionally in microgrid systems battery storage provides these services at high rates. In smart microgrid environment an efficient regulation service can be provided using SEV. The results reveal that grid integration of electric vehicle has significant economic potential to provide regulation up and down without compromising on the driving schedule. The regulation price of the region plays an important role in deciding the cost of grid integration of vehicle. GIV optimizes the overall performance of microgrid by enabling better utilization of microgrid resources. Grid integration of vehicle greatly reduces the cost of ownership of electric vehicle and hence proves to be beneficial to the vehicle owner who receives revenue for providing regulation services without any extra expanses.

The degradation cost of electric vehicle batteries is due to charging and discharging for two different services, hence this cost has to be separated into two components i.e. the cost due to battery degradation for mobility service of the vehicle and the cost due to power regulation service. Presently the cost of battery degradation is cumulatively combined with the contract payment of availability and hence customer is paid off this cost as a part of the revenue. However the design of revenue structure for this kind of electricity generation/service can be a new research idea. Design and development of coordinated, combined BSS and GIV operation is a part of our future work, which can help the evolution of advanced distribution system with active loads. The views of consumers/agencies/experts [28, 29] regarding electric vehicle usability and consumer behaviour in future will be an important aspect of this research.

Appendix

Table 5 Constants used in Numerical Analysis

S.No.	Quantity	Value
1	R_{d-c}	0.90
2	C_{en}	9.6 $\$kWh^{-1}$
3	P_{Conv}	240,192,144,96,40 kW
4	$H_{ch,}/H_{disp}$	4 hrs.
6	C_{pel}	0.031 $\$kWh^{-1}$
7	η_{conv}	0.73
8	E_S	1920,1536,1152,768,320kWh
9	C_c	60.4 $\$kWh^{-1}$
10	C_l	7.55$\$kWh^{-1}$
11	t_l	2hrs.
12	L_s	10yrs.
13	D	10 %
14	N	10yrs.
15	P_{cap}	0.004$\$$ kWh^{-1}
16	P_{el}	0.031,0.10117 $\$kWh^{-1}$
17	P_{veh}	3.3kW

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