A ROBUST D-FACTS BASED METAHEURISTIC CONTROL SYSTEM FOR BATTERY CHARGING SCHEME

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ABSTRACT

This paper presents a Li-ion battery storage system provided with a supercapacitor as a backup micro-fuel interface scheme to AC/DC power system that can be utilized during maximum demand circumstances. Distributed flexible AC transmission system (D-FACTS) based–switched filter compensator (SFC) scheme is proposed to ensure energy efficient of battery charging scheme. A dynamic multi-level error-driven control strategy is proposed to guarantee better power quality performance in terms of fast charging of the battery storage system, voltage enhancement and stabilization of the DC and AC buses, improvement of power factor of AC buses, inrush current minimization and harmonic current distortion reduction. The proposed SFC is controlled by means of a multi-level functional error-driven inter-coupled weighted modified proportional-integral-derivative (WM-PID) controller. Grey wolf optimization is employed for tuning PID controller gains in terms of change at state of charge (SOC) and to reflect the performance of the battery storage system. MATLAB/Simulink software is used to model and simulate the distributed FACTS scheme. The results discuss the effectiveness and robustness of the proposed SFC topology.

INTRODUCTION

In recent years, electric vehicles (EVs) technology is emerging to offer an effective way for reduction of fossil fuel consumption, global energy demand and global warming. Consequently, it is a promising solution to use the different type of green-plugged-in hybrid EVs which can be energized from renewable energy-based power generation technologies that is called grid-to-vehicle (G2V) where the voltage is imposed by the grid and the current by the EV battery charger. Also, it can feed a grid as vehicle-to-grid (V2G) scheme. These technologies have several merits such as low noise level, zero emission (when driving on batteries), fuel efficient, and high-efficiency in transportation systems [1].

Consequently, topologies of switched filter compensator (SFC) have been applied for EVs application to enhance voltage stability, mitigate harmonics, compensate any reactive power shortage, and energy sustainability. An efficient design of permanent magnet DC drive scheme for EVs fed on a hybrid lithium-ion battery-fuel cell green energy sources based on SFC has been presented in [2]. A novel hybrid filter topology for photovoltaic system used for energizing V2G scheme is discussed in [3]. These compensation topologies have their own advantages and disadvantages. In addition, it can be noticed that optimal design of these compensators is not presented nor discussed.

In this paper, an advanced FACTS structure based–switched filter compensator (SFC) is provided with a boost converter for G2V battery charger applications to enhance power quality (PQ) issues, reduce total harmonic distortion (THD), minimize AC and DC inrush currents, and improve voltage stability. A dynamic control strategy is proposed using a three-level error driven weighted modified proportional-integral-derivative (WM-PID) controller to drive the compensator. Besides, a boost converter is also controlled by an additional three-level error-driven PID controller to ensure a fast charging of the storage system.

Grey Wolf Optimization (GWO) algorithm is utilized to optimize tuning values of the PID controllers' gains. The results show the features of the proposed compensator in terms of state of charge (SOC) of the battery as a performance indicator of the storage system and THD analysis. Finally, the influence of the introduced SFC-based control strategy has been tested by offline time-domain simulations in MATLAB/Simulink platform.

The rest of the paper is organized as follows: first, the system under study is described; next, details of the proposed control scheme, design procedure, and formulations for optimizing/tuning of the controllers' gains are outlined. Finally, the simulation results, conclusions and work extensions are discussed

THE SYSTEM UNDER STUDY

The system configuration

Figure 1 illustrates the studied system of the G2V scheme as a single line diagram (SLD).

This scheme comprises of a Li-Ion battery provided with supercapacitor (C_1) that is connected to the DC side to settle frequent charging problem and absorb energy during the regenerative breaking. The SFC topology is connected to the AC bus V_r through bridge rectifier as a capacitor compensator (C_f) for reduction of THD, limitation of inrush currents and ensuring energy sustainability of the AC side during fast charging of Li-Ion batteries. R_1, L_1 represents the cable impedance on the DC side. DC filter that includes R_0 and L_0 reduces transient over voltages as well as limiting inrush currents introduced by DC-DC boost chopper switching. The detailed specifications of the system components are provided in the Table 1.

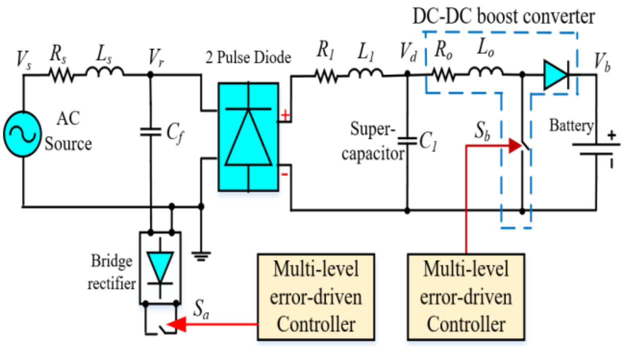


Figure 1: The SLD representation of the G2V system.

Lithium-ion battery modelling

Due to the outstanding features of the lithium metal, Lithium-ion (Li-ion) batteries rapidly penetrated into high-performance EVs schemes. Compared to other batteries, Li-ion batteries have higher efficiency, specific power and energy densities, less self-discharge rate, and longer lifetime. Also, the cost is reasonable. The electrical equivalent circuit model consists of an ideal voltage source V_{oc} and an internal resistance R_o as illustrated in Figure 2(a) in which I_L is the load current and V_t *is* battery terminal voltage. The electrical equation that represents this model is given by:

$$V_t = V_{oc} - I_L R_0 \tag{1}$$

The open circuit voltage V_{oc} is extremely correlated to the SOC of the battery. The SOC is between 0 and 100% The SOC is expressed as given by Eq. (2):

$$SOC = 100(1 - \frac{1}{Q}\int_0^t i_L(t)dt) \tag{2}$$

where Q represents maximum battery capacity (Ah). The specification of the battery is illustrated in the Table 1.

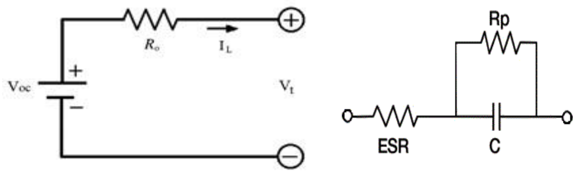
Supercapacitor modelling

The integration of battery system with supercapacitor (SC) can solve many shortcomings such as battery sizing, causing an over-dimensioned battery pack and less use of energy. This integration provides fast charging, enhance the battery performance by increasing its lifecycle, reducing the energy losses and limiting the temperature rise inside the battery.

TABLE 1: The detailed specification of the system components

System Part	Specifications
AC source	240V AC, 60 Hz
Battery storage	300V DC, 3750 Ah
Supercapacitor	300 V, 0.1 F
R_s	0.1 Ω
L_s	3 mH
Cf	550 µf
$R_1 = R_0$	0.05 Ω
$L_1 = L_0$	3 mH

The chosen model of SC as illustrated in Figure 2(b) has been presented by [4]. The parameters of the presented SC consist of series resistance (ESR), parallel resistance (R_P), and capacitance (C).
ESR is the resistance in the electrodes, contacts, and in the electrolyte. R_P is an inner equivalent parallel resistance and gives the leakage current when there are no external connections to its terminals. The parameters of the SC are given in the Table 1.



(a) (b)

Figure 2: Li-ion battery modelling

THE PRESENTED FILTER SCHEME

The introduced SFC structure is a switched/modulated filter that is allocated on the AC side of the receiving voltage V_r of G2V scheme and acts as a capacitor compensator and PQ conditioner. The AC side of an uncontrolled rectifier is coupled with fixed capacitor that is connected in parallel. This combination namely SFC as shown in Figure 1.
Using one complementary electronic switch such as insulated gate bipolar transistor (IGBT) or metal oxide semiconductor field effect transistor (MOSFET) which is controlled by means of a three-level error-driven provided with a modulated PID controller, two functioning modes are provided, namely a capacitor and a filter to mitigate harmonics, improve power factor, and enhance power quality.

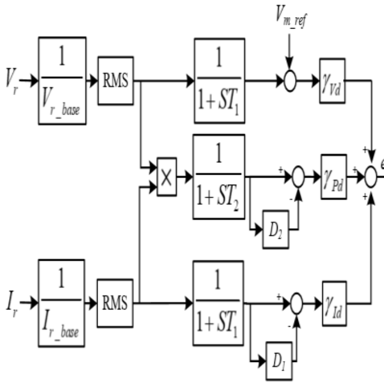
Modelling of multi-level regulation

The presented micro-fuel interface scheme of AC/DC power system is controlled by three-level control systems which the main function of three-level is modifying the errors of voltages and currents of both buses on AC and DC sides of the 2-pulse diode. In this work, the three-level with time de-coupled error-driven WM-PID controller is introduced in (Figures 3(a)-3(b)).

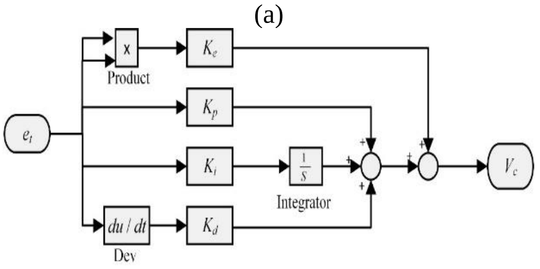
Two error signals e_{t1}, e_{t2} which are produced from three-level regulators, drive the weighted modified pulse width modulation (WM-PWM) for controlling pulsating signal injection sequence to MOSFET/IGBT switches. One of this electronic MOSFET/IGBT switch S_a drives the presented SFC and the other S_b drives the boost converter. The detailed parameters of the SFC and the booster components are provided in the Table 2.

TABLE 2: The detailed specification of SFC and boost converter

SFC		Boost converter	
System Part	Specification	System Part	Specification
V_{r_base}	240V	V_{b_base}	300V
I_{r_base}	62.5A	I_{b_base}	50A
V_{m_ref}	1 pu	V_{m_ref}	1 pu
$\gamma_V = \gamma_I$	1	$\gamma_V = \gamma_I$	1
γ_P	0.5	γ_P	0.5
$T_1 = D_1$	10 ms	$T_1 = D_1$	10 ms
$T_2 = D_2$	20 ms	$T_2 = D_2$	20 ms
PWM frequency	2750 Hz	PWM frequency	3000 Hz



(a)



(b)

Figure 3: The proposed scheme control strategy: (a) Three-level error-driven PID of SFC and (b) Weighted and modified PID controller with squared loop error

The inputs of three-level regulator for switching S_a of the presented SFC are the current and voltage signals of bus V_r. The error signals of voltage, current and power are given by Eqs. (3)-(5).

$$e_{Vr} = \frac{V_{m\_ref} - V_r(\frac{1}{1+ST_1})}{V_{r\_base}} \quad (3)$$

$$e_{Ir} = \frac{I_r}{I_{r\_base}}\left(\frac{1}{1+ST_1}\right)\left(1 - \frac{1}{1+ST_1}\right) \quad (4)$$

$$e_{Pr} = \left(\frac{V_r}{V_{m\_base}} x \frac{I_r}{I_{m\_base}}\right)\left(1 - \frac{1}{1+ST_2}\right) \quad (5)$$

The inputs of three-level regulator for switching S_b of the booster are the current and voltage signals of bus V_b. The error signals of voltage, current and power are given by Eqs. (6)-(8).

$$e_{Vb} = \frac{V_{m\_ref} - V_b(\frac{1}{1+ST_1})}{V_{b\_base}} \quad (6)$$

$$e_{Ib} = \frac{I_b}{I_{b\_base}}\left(\frac{1}{1+ST_1}\right)\left(1 - \frac{1}{1+ST_1}\right) \quad (7)$$

$$e_{Pb} = \left(\frac{V_b}{V_{b\_base}} x \frac{I_b}{I_{b\_base}}\right)\left(1 - \frac{1}{1+ST_2}\right) \quad (8)$$

The total errors e_{t1} and e_{t2} are the summation of the three different errors, including voltage stability, current limiting and dynamic power loops of the proposed SFC and the booster which are given by Eqs. (9) and (10), respectively.

$$e_{t1} = \gamma_{Vr}\,(e_{Vr}) + \gamma_{Ir}\,(e_{Ir}) + \gamma_{Pr}\,(e_{Pr}) \quad (9)$$

$$e_{t2} = \gamma_{Vb}\,(e_{Vb}) + \gamma_{Ib}\,(e_{Ib}) + \gamma_{Pb}\,(e_{Pb}) \quad (10)$$

Finally, in the time domain the following formulas $V_{c1}(t)$ and $V_{c2}(t)$ are the contribution signal of the WM-PWM of the SFC and the booster for the PID controllers, respectively.

$$V_{c1}(t) = K_{e1}\,(e_{t1}(t))^2 + K_{p1}\,e_{t1}(t) + K_{i1}\int_0^1 e_{t1}(t)dt + K_{d1}\frac{d(e_{t1}(t))}{dt} \quad (11)$$

$$V_{c2}(t) = K_{e2}\,(e_{t2}(t))^2 + K_{p2}\,e_{t2}(t) + K_{i2}\int_0^1 e_{t2}(t)dt + K_{d2}\frac{d(e_{t2}(t))}{dt} \quad (12)$$

FORMULATION OF THE OBJECTIVE FUNCTION AND OPTIMIZATION

The fitness functions

To fine-tune the proposed SFC-PID controllers' gains (K_{p1}, K_{i1}, K_{d1}, and K_{e1}) provided with the boost converter that is also provided with the booster; the fitness function is defined as:

$$\min(J_1) = \min(0.5\int e_{t1}^2\,dt + 0.5\int e_{t2}^2\,dt) \quad (14)$$

where J_1 is the total error of controller of the proposed SFC with the booster. Besides, the optimization problem is subjected to the following constraints.

Constraints

The voltage level at the load bus is constrained between its minimum and maximum values, thus:

$$0.95 \le V_L \le 1.05 \quad (15)$$

The THD of the voltage (THD_v) of the load bus, given by Eqn. (16), thus

$$THD_v = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} \quad (16)$$

$$THD_v < THD_{v,max} \quad (17)$$

The THD of the current (THD_i), given by Eqn. (18), thus

$$THD_i = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \quad (18)$$

$$THD_i < THD_{i,max} \quad (19)$$

Grey Wolf Optimization (GWO)

In 2014, Mirjalili et al. developed a new meta-heuristic algorithm known as Grey Wolf Optimizer (GWO) for solving many multi-modal functions [5]. It is inspired by the communal behaviour of grey wolves. The grey wolves possess a strong social hierarchy which is employed in this algorithm. The wolves normally live in a group known as pack. They are mainly divided in four hierarchical level named as alpha, beta, delta and omega. Alpha wolves are on the top level and are responsible for decision-making. The next order in the pack is the betas. The beta wolves support the alphas in decision making and spread the order of the alphas inside the group. The next layer of this graded structure is the deltas. They mainly act as caretaker and sentinel of the group. The last level of this pyramid structure belongs to omega wolves and they are the least priority member in the group. There are mainly three phases of the grey wolves namely tracking, encircling and hunting. The encircling activities of the wolves can be mathematically expressed as:

$$\vec{D} = \left|\vec{C}.\vec{X}_P(t) - \vec{X}(t)\right| \quad (20)$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}.\vec{D} \quad (21)$$

$\vec{X}$ denotes the current position of the grey wolf and t indicates the current iteration. The vectors $\vec{A}$ and $\vec{C}$ are given by following equations:

$$\vec{A} = 2\vec{a}.\vec{r_1} - \vec{a}; \qquad \vec{C} = 2.\vec{r_2} \quad (22)$$

where the components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and $\vec{r_1}, \vec{r_2}$ are random vectors in [0,1]. The hunting nature of alpha, betas and deltas are mathematically expressed as:

$$\vec{D_\alpha} = \left|\vec{C_1}.\vec{X}_\alpha - \vec{X}\right|, \vec{D_\beta} = \left|\vec{C_2}.\vec{X}_\beta - \vec{X}\right|, \vec{D_\delta} = \left|\vec{C_3}.\vec{X}_\delta - \vec{X}\right| \quad (23)$$

$$\vec{X_1} = \vec{X}_\alpha - \vec{A_1}.(\vec{D_\alpha}), \vec{X_2} = \vec{X}_\beta - \vec{A_2}.(\vec{D_\beta}), \vec{X_3} = \vec{X}_\delta - \vec{A_3}.(\vec{D_\delta}) \quad (24)$$

$$\vec{X}(t+1) = \frac{\vec{X_1}+\vec{X_2}+\vec{X_3}}{3} \quad (25)$$

The general flowchart of GWO algorithm is shown in Figure 4 and for more details about the GWO algorithm; readers are referring to [5].

DIGITAL SIMULATION RESULTS

Two scenarios for examining the introduced topology is presented, including changing in the SOC of battery storage, and analysis of THD. The results are provided at the receiving bus "*r*" where the simulations are done for the SFC by applying GWO.

Changing in battery charging status

The various power quality indices such as the voltage, current, active and reactive powers under the variation of battery charging status are illustrated. The SOC is considered at 10% charging level. The results have been illustrated in the separate at the receiving bus "*r*".

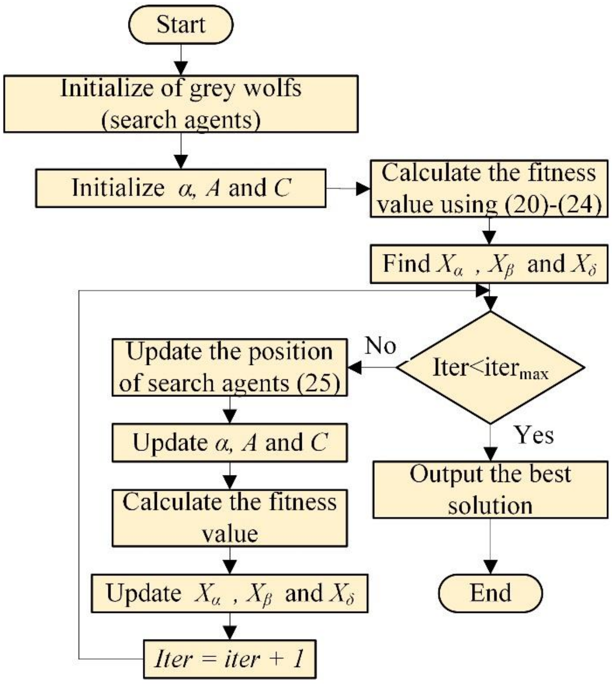
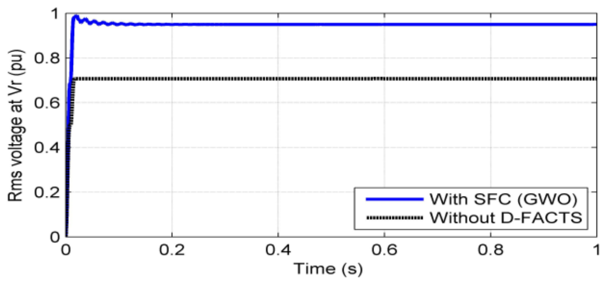


Figure 4: Flowchart of grey wolf optimization algorithm.

Battery charging status (10%)

As shown, the proposed SFC topology during 10% of battery charging status has an affirmative influence on enhancing the PQ issues. It is cleared from Figure 5 that the current at the bus '*r*' and consequently, the reactive power is decreased. In addition, the rate of change of the voltage is smoothly approaching to 1 pu.

The values of PID controllers' gains for SFC in addition the boost converter are illustrated in Table 3 under 10% battery charging status.



(a)

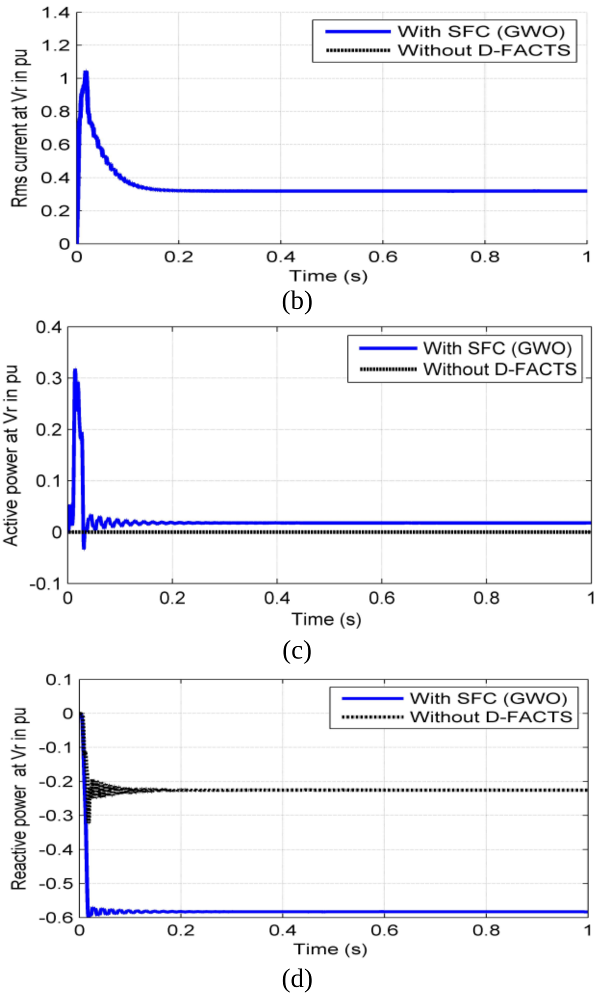


Figure 5: Simulated results (V_{rms}, I_{rms}, P, Q) at the V_r bus before and after compensation under battery charging status (10%): (a) Rms voltage, (b) Rms current, (c) Active power, and (d) Reactive power.

Analysis of harmonic distortions

The THD is an important index to detect the level of harmonic distortion in voltage or current waveforms. Accordingly, the THDs of the voltage and current at the AC buses, with and without the proposed SFC, have been analysed.

An analysis of voltage and current harmonic in term of the THD is provided in Table 4. It is clear that the voltage harmonics are significantly reduced to an acceptable level within the allowable limit set by the IEEE standards [6].

CONCLUSIONS

In this work, an economic distributed FACTS-based switched filter was proposed to improve power quality (PQ) of a battery charging system. A three-level error-driven adapted PID controller was utilized for driving the switching signal of the SFC-FACTS device and DC/DC boost converter alike. Also, it was provided with additional error-squared loop to guarantee fast response for the sake of efficient energy utilization. The SFC scheme had a key role in the mitigation of harmonics, stabilizing voltages, compensation of reactive power, as well as improving the PQ in the battery charger utilized for a G2V scheme of EVs. Also, the results illustrated the efficiency of the introduced optimal SFC scheme.

TABLE 3: PID controllers; gains for SFC and D-STATCOM during battery charging status (10%)

Controller gains	**SFC-PID with the booster**	
	SFC-PID (K_{p1}, K_{i1}, K_{d1}, K_{e1})	Booster-PID (K_{p2}, K_{i2}, K_{d2}, K_{e2})
K_p	96.4543	32.8188
K_i	23.1837	14.0138
K_d	7.5860	6.5021
K_e	0.5831	5

TABLE 4: THD values at the Vr bus

THD value (%)	Without D-FACTS	With SFC
voltage at V_s bus	0.1	0.00
current at V_s bus	27.45	10.69
voltage at V_r bus	14.25	1.36
current at V_r bus	21.57	8.36

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