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Applications of Energy Storage to Improve Performance of Utility Grids in Presence of Renewable Energies and Electric Vehicles

PhD Dissertation Booklet

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1. Introduction

It is common knowledge that traditional energy sources such as gasoline, coal, and gas have been widely used in the past, and they are still utilized today in electricity production and transportation in addition to other uses. The widespread application of these energy resources, especially in meeting the world's population's demand for electric power, has had negative environmental consequences, such as air pollution and greenhouse gas emissions (GHG) which cause the climate changes [1]. Furthermore, energy consumption is rising continuously due to the rapid industrial and technological growth, especially in developing countries. Since vast volumes of energy are needed to sustain industrial system activities, industrial growth has a direct impact on energy demand. As a result, renewable energy sources (RESs) and electric vehicles (EVs) must be investigated in order to mitigate the negative impacts of traditional energy sources and to provide opportunities to supplement scarce energy supplies. The intermittent nature of the RES power generation could cause severe fluctuations of both voltage and frequency of power system and lead to the reduction of the inertia response. Moreover, the impacts of electric vehicles on the electrical power network in the presence of renewable energy sources is a field to be studied in depth. Especially because in recent years the number of electric vehicles has increased considerably in order to reduce the emission of CO_2 and fossil fuel consumption to reach environmental cleanliness.

To solve all the above issues, a control method depending on controlling the energy storage of an energy storage system (ESS) has been recently adopted. Fortunately, recent developments in ESSs will serve as a backup mechanism for traditional power plants. As a result, RESs and EVs will be much easier to incorporate into the network, particularly when combined with the right ESS. ESSs such as batteries [2], flywheels [3], superconducting magnetic energy storage (SMES) [4], etc. offer an important substitute solution to overcome the above issues. Choosing the best type of energy storage system depends on the target application. In order to achieve the best solution, efficiency, life span and response time must be considered. The SMES based on the appropriate control method is favorable compared to other energy storage systems. There are a lot of control techniques that have been applied in the relative literature such as PI, sliding mode control, and FLC, the FLC has found its way for power system application due to its promising advantages.

This thesis focuses on the development of an efficient and robust controlled superconducting magnetic energy storage (SMES) in different applications to improve the performance of the utility grid. The SMES is proposed with power levelling strategy application in the presence of wind turbine during a wind gust. Moreover, SMES is proposed to improve the microgrid stability during various events in the presence of wind power based on different types of generators and also a photovoltaic (PV) system. Furthermore, an adaptive coordination control method is proposed between SMES and EVs to optimize the characteristics of EV charging/discharging and to enhance the charge and discharge processes of EVs during off-peak and peak loading periods. In addition, the SMES is used with energy management application in the presence of EVs and RESs. Finally, the SMES is used in a virtual synchronous generator (VSG) compensation application in a modern power system.

2. Thesis Objectives

The main objective of the thesis is to develop an efficient and robust controlled-SMES in different applications to improve the performance of the utility grid. SMES is a large superconducting coil capable of storing electrical energy in the magnetic field generated by DC current flowing through it. The direct storage of electrical energy in the field of a superconducting coil allows access time in the range of milliseconds, while the duration and the number of charge/discharge cycles have no influence on the life time of SMES. Moreover, the charge/discharge efficiency is very high [5].

Due to its rapid discharge capabilities, the technology has been implemented on electric power systems for pulsed power and system stability applications [5]. SMES has several benefits such as [6]:

1. It improves power quality for critical loads and provides carryover energy during momentary voltage sags and power outages,
2. It improves load leveling between RESs (e.g., wind and solar) and the transmission and distribution networks,
3. It is environmentally beneficial as compared to batteries; as superconductivity does not rely on a chemical reaction and no toxins are produced in the process,
4. It enhances transmission line capacity and performance – SMES features a high dynamic range, an almost infinite cycling capability, and an energy recovery rate close to 100%,
5. Ultra-high field operation enables the long-term storage system in a compact device with cost advantages in material and system costs,
6. It provides frequency support (spinning reserve) during loss of generation,

7. It enhances transient and dynamic stability, and
8. VAR compensation.

The advantages of SMES over other ESSs are [6]:

1. The direct storage of electric energy in the field of a superconducting coil allows access times in the range of milliseconds,
2. The duration and number of charge/discharge cycles has no influence on the lifetime of SMES,
3. A charge/discharge efficiency of up to 95% can be obtained,
4. The SMES unit is highly efficient due to its low power loss, and
5. Electric currents in the coil encounter almost no resistance and the unit has no moving parts.

The major drawback of SMES is the high cost of implementation and the environmental issues associated with strong magnetic fields.

Moreover, in this thesis FLC is used because the FLC is quick to understand where the ideas of FLC are basic, FLC is flexible where it can emerging fuzzy structures to be used to their features by utilizing new information to set rules, the impact of incorrect data on FLC is not large where the calculation accuracy errors influence device efficiency little, FLC is suitable for nonlinear systems of subjective complexity, FLC is based on the experience and actions of the system, FLC can be used easily with conventional control systems to improve efficiency, FLC is built on the normal human language and lets new rules be introduced, exceptions and new behaviors to set fuzzy structures.

Therefore, the SMES system based on FLC is one of the preferred options in power system applications. In this thesis, the behavior of controlled-SMES applications in power leveling strategy in distribution systems, and in a microgrid in grid-connected mode during various events are studied. Moreover, the application of SMES in adaptive control method with EVs, and in energy management with RESs and EVs are tested. Besides, this study proposes an application of SMES in VSG. Therefore, the research objectives, which will be accomplished in this thesis, can be defined as follows:

2.1 Application of SMES Technology in Power Levelling Strategy of Wind Gust

The main goal is to feed constant active power from the wind connected with the balanced/unbalanced distribution system during weather changes. A FLC-SMES has been applied to achieve active power sharing. The damping of voltage fluctuation depends on the SMES reactive power, which is controlled by VSC. The proposed control method is also used to mitigate the intermittent power generated from RESs. The FLC has two inputs and one output: the first input is the power variation, wind speed variation, or PV irradiance variation that based on the application type. The second input is based on the SMES current, which preserve on the SMES current within allowed limits. The output is the SMES duty cycle, which controls the charging/discharging process of the SMES coil through a DC-DC chopper. The proposed control technique was effective in keeping the real power transfers to the microgrid at constant value during weather changes. This resulted in minimizing the fluctuation of the microgrid frequency and smoothing the output power from the DSGs and the grid. Moreover, the voltage profiles were successfully kept within the prespecified limits during weather changes.

2.2 Application of SMES Technology in Microgrid-Grid-Connected Mode during Various Events

Microgrid is considered the optimal solution for supplying remote areas with the required electrical power. Microgrid systems apply one or more RESs, such as wind turbines and PV systems, etc. Due to the intermittent nature of RESs, power and voltage fluctuations have appeared accordingly at the connection point with the utility power grid. Moreover, the transient events such as an increase in the loads causes fluctuation of frequency and voltage of power systems. In addition, there is a special type of load called PPL. When PPL is integrated into the power system, it leads to high fluctuations in the frequency and voltage at the PCC. Moreover, the DFIG and PMSG are used for improving the power system stability in the presence of the SCIG as existing generation unit. This can be used to increase the penetration level of the generation better than using SCIG only. Also, this method demonstrates the application of SMES to enhance the voltage and frequency stability of power systems fed from SCIG, PMSG, and DFIG wind turbines during transiently load events. By using PMSG, DFIG and SMES with SCIG, the power system stability can be improved and the performance is still more reliable without removing the SCIG from the system. A two-quadrant DC-DC chopper using an IGBT achieved the SMES active power control technique. A FLC is used to determine the duty cycle to control the charging/discharging process of the SMES coil through a DC-DC chopper. The proposed control method is examined under various events such as load transition, and wind power variations, and PPL. Multiple types of wind generators are utilized in this study like SCIG, DFIG, and PMSG.

2.3 Application of SMES Technology in Adaptive Coordination Control with EVs

Due to the enormous increase in the interconnection of EVs into utility power grids, more and more challenges are arising in modern power systems. To handle these challenges, many attempts have been proposed to achieve the satisfactory performance of EV charging/discharging, the improvement of utility power grids operation, and an adaptive coordination strategy for the EV–grid connection. The SMES unit plays a vital role in this process by injecting/absorbing the energy into/from the grid, including EVs. The proposed coordination method can achieve a better performance of EV charging/discharging. Moreover, the cooperative operation with SMES and the reliability improvement of the utility power are preserved using the proposed coordination strategy. The EVs charging/discharging with SMES operation category is proposed to optimize the characteristics of EVs charging/discharging. Where, an adaptive coordination method based on FLC for EVs and SMES to enhance the charge and discharge processes of EVs during off and on peak loading periods. FLC is utilized to organize the charging/discharging process for both EVs and SMES. The SoC of SMES and EVs is considered as the input for the FLC of EVs besides the electricity price (EP) signal. The controlled charging/discharging with SMES achieves the best performance, which minimizes power loss, injects reactive power to the grid, reduces the reactive power required from the grid, keeps the voltage at 1.0 pu, reduces peak power, and reduces the active power required from the grid.

2.4 Application of SMES Technology in Energy Management with EVs and RESs

To achieve the advantages of EVs, they can be fueled through the RESs such as PV and wind systems to reduce fuel costs and pollution. A PV system and a wind system can be used as power sources for electrical appliances and a charger for EVs. To face the growing load demand with a continuous reduction in fossil fuels, the PV and wind systems offer an alternative solution. The proposed study considers the targeted renewable energy powered utility grids with installed ESSs. PV and wind energy has been utilized in a case study for the RES with considering its stochastic characteristics and its continuous fluctuations with irradiance and wind speed. The various aspects of PCC voltage fluctuations, reactive power support, leveling active power of the peak period, and power losses are considered. Moreover, FLC systems are proposed for controlling EVs and the SMES device. The energy management between the installed EVs, SMES, wind turbine, PV, and utility grid side is achieved through the coordination of the FLC systems. The main problem is the difference in thinking and purposes between the EV owners and the grid side. From the point of view of the EV owner, it is essential to provide the electricity to charge the EV at an acceptable price at any time. Meanwhile, from the point of view of the electricity grid, the energy management will face more challenges because of the probability of overlap between the peak residential load period and the EV charging period. Therefore, it is necessary to propose coordinated control charging techniques for EVs.

2.5 Application of SMES Technology in VSG

In the light of SMES considerations, the SMES system is used with VSG power management technology. In this application, the SMES is used to imitate the needed inertia power from the VSG in a short period to handle the issues that result from the high penetration levels of RESs. The implementation of the SMES-based VSG can charge/discharge large amounts of power in a short amount of time, thus compensating for the unbalanced power as well as frequency/voltage fluctuations. As a result, advanced RESs will achieve greater flexibility and stability. As the load fluctuates significantly, the frequency and voltage fluctuations can be very high, forcing power systems into an unpredictable state. As a result, using a VSG-based SMES is important to compensate for the power system and eliminate frequency and voltage fluctuations.

3. Thesis Outline

This thesis is divided into eight chapters as follows:

Chapter 1: This chapter describes the background, motivations, contributions, significance and the outline of the research.

Chapter 2: This chapter presents the detailed modeling of SCIG, DFIG, PMSG based wind turbine, PV generation system model, EVs model, SMES model and configuration, and the FLC technique.

Chapter 3: This chapter introduces a proposed FLC-SMES technique to achieve power-leveling strategy; alleviate frequency and voltage fluctuations of a balanced/unbalanced IEEE 33 bus distribution system resulting from the intermittent generations of wind turbine.

Chapter 4: This chapter describes a proposed FLC-SMES technique to enhance microgrid performance in a grid-connected mode during various events such as load transition, wind power variations, and PPL. Multiple types of wind generators are utilized in this study like SCIG, DFIG, and PMSG.

Chapter 5: This chapter offers a coordination control strategy between SMES and EVs in the charging/discharging process including the charging price of EVs and SoC to achieve a better performance of EV charging/discharging. Moreover, the cooperative operation with SMES and the reliability improvement of the utility power are preserved using the proposed coordination strategy.

Chapter 6: This chapter proposes the energy management between the installed EVs, SMES, wind, PV, and utility grid side, based on the coordination of the FLC systems, which achieve the advantages of EVs that can be fueled through the RESs such as PV and wind systems to reduce fuel costs and pollution.

Chapter 7: This chapter proposes a new application of SMES with VSG to compensate for frequency and voltage fluctuations in the power system.

Chapter 8: This chapter provides a summary of each chapter followed by the final list of contributions for the thesis. Future research directions are addressed for possible improvement and further SMES system applications.

In order to present the overall picture and help to understand the contents and the distribution of contributions between the different chapters, Figure 1 presents the overall workflow in the dissertation, which has three parts, namely, Part I, Part II, and Part III.

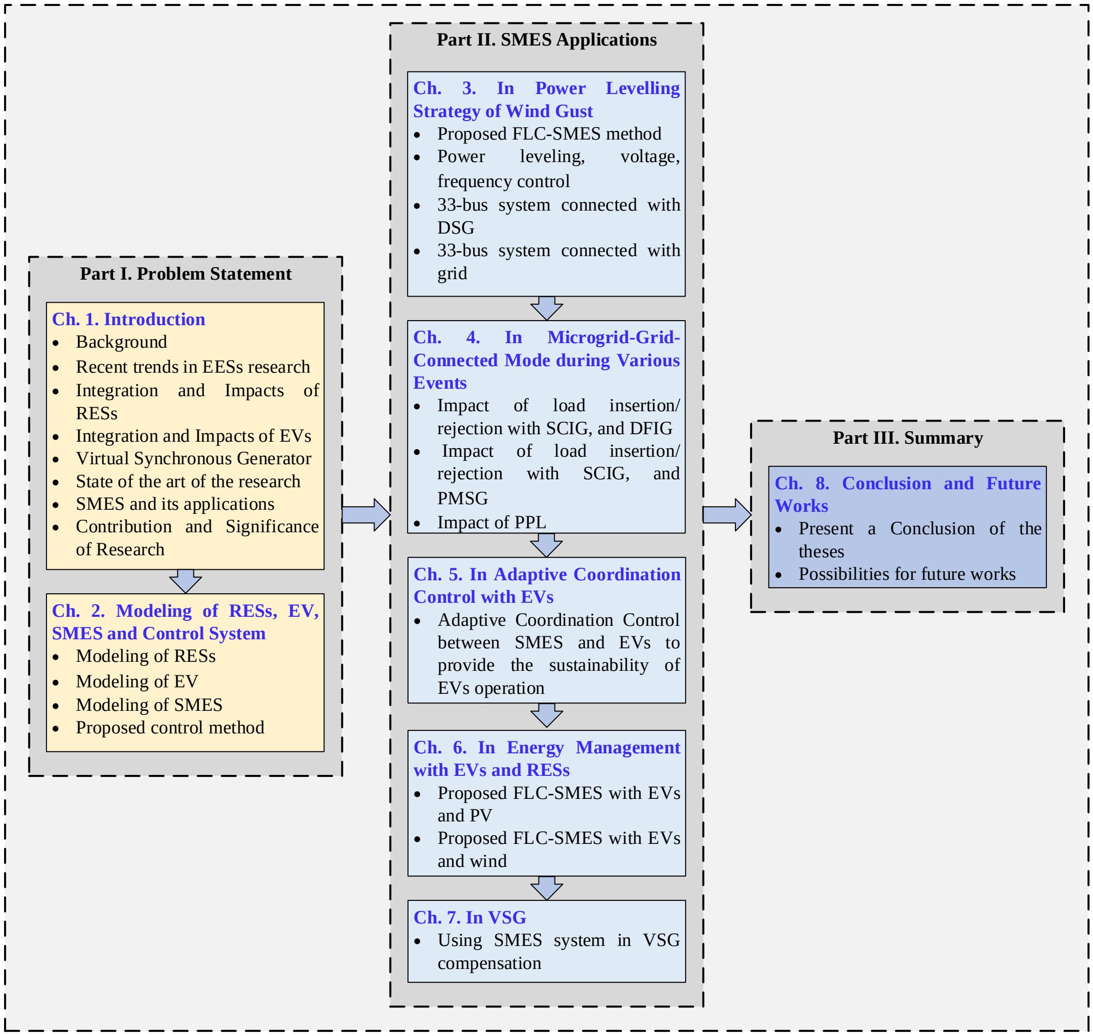

Figure 1. Dissertation research directions.

4. Theses

4.1 Thesis 1

"I have proposed a developed fuzzy logic controller (FLC) technique with SMES to utilize the application of SMES in power levelling strategy of a distribution system in the presence of a wind system in the case of wind gusts. The proposed method is based on achieving the power balance between the load and generation during a wind gust. The DC-DC chopper and VSC of SMES system are controlled to provide the power sharing, and consequently to minimize the voltage and frequency fluctuations. I have used the IEEE 33-bus distribution system as a case study, once with a diesel synchronous generator (DSG) and once with grid. I proved the effectiveness of the proposed control method with SMES by achieving the target in the power levelling application of a balanced/unbalanced distribution system. Moreover, the proposed control technique was effective in keeping the real power transfers to the system at a constant value during weather changes. This resulted in minimizing the fluctuation of the microgrid frequency and smoothing the output power from the DSGs and grid. Moreover, the voltage profiles were successfully kept within the prespecified limits during the weather changes."

The related work is presented in Chapter 3 of the dissertation and has been published in [J4] and [J11].

4.2 Thesis 2

"I have tested the impact of a various events such as the intermittent generation of RESs (i.e., wind systems based DFIG and PMSG), load step change, and pulsed power load (PPL) on microgrid with the proposed control method based on SMES and FLC. The SMES has proven highly effective in overcoming all these problems in the microgrid, by controlling the charging/discharging of the SMES system. Due to the various events, power and voltage fluctuations have appeared accordingly at the connection point of the microgrid and the utility power grid. In addition, I proposed control method based on FLC-SMES to demonstrate the application of SMES to enhance the voltage and frequency stability of power systems, which were fed from SCIG, PMSG, and DFIG based on wind turbines, and during transient load events and also PLL. I have used a different types of wind generators such as PMSG, DFIG and SCIG with SMES system. I have proved that the power system stability can be improved and the overall system performance became more reliable."

The related work is presented in Chapter 4 of the dissertation and has been published in [J3], [J12], and [C1].

4.3 Thesis 3

"I have proposed an efficient coordinated control method between EVs and SMES to achieve a satisfactory performance of EV charging/discharging, the improvement of utility power grid operation, and an adaptive coordination strategy for the EV–grid connection. I have demonstrated that the proposed coordination method can achieve a better performance of EV charging/discharging. Moreover, the cooperative operation with SMES and the reliability improvement of the utility power are preserved using the proposed coordination strategy. The controlled charging/discharging with SMES operation category has been proposed to optimize the characteristics of EVs charging/discharging. An adaptive coordination method based on FLC for EVs and SMES is proposed to enhance the charge and discharge processes of EVs during off and on peak loading periods. The state of charge (SoC) of SMES and EVs is considered as the input for the EVs' FLC besides the electricity price signal. The results have proven that the proposed method can minimize power loss, injects reactive power into the grid, reduces the reactive power required from the grid, keeps the voltage at 1.0 pu, reduces peak power, and reduces the active power required from the grid."

The related work is presented in Chaptre 5 of the dissertation and has been published in [J5].

4.4 Thesis 4

"I have applied a novel algorithm to achieve the energy management of a system integrating wind turbine, PV, SMES sources, also considering EVs coordinated by an FLC system. I have used the power at the PCC and the electricity price as signals for the proposed energy management control method. The PV system and the wind system can be used as power sources for electrical appliances and for EVs. The proposed study considers the targeted renewable energy powered utility grids with installed ESSs. The PV and wind energy have been analyzed as examples for the RESs, considering their stochastic characteristics and the continuous fluctuations of irradiance and wind speed. The various aspects of PCC voltage fluctuations, reactive power support, leveling active power of the peak period, and power losses have been improved with the proposed method. I have demonstrated that that the proposed algorithm is a suitable energy management technique for the PV, wind, SMES, and EV system, and achieve the best performance between them."

The related work is presented in Chapter 6 of the dissertation and has been published in [J6], [J8], and [C2].

4.5 Thesis 5

"In this thesis, I have proposed a novel control method with virtual synchronous generator (VSG) based on a SMES system in the time domain. The proposed method feeds the modern power system with inertia during unpredictable events and improves the frequency and voltage response. I have computed the command active power of the SMES system according to the state of the frequency deviation in the VSG model with a PI-controller, considering the virtual inertia and damping factors. Meanwhile, the reactive power control is achieved by Q-Droop control. The obtained results prove the effectiveness of the proposed method to support the modern power system with inertia, and to improve the transient and steady state behavior of frequency and voltage."

The related work is presented in Chapter 7 of the dissertation and has been published in [J1] and [J7].

5. Significance and Practical Applicability of the Results

The use of ESSs with the modern power system has become a necessity due to their ability to reduce the side effects of the RESs and EVs integration, increase the stability of the modern power system, improve the power system performance, providing higher reliability, and improve overall efficiency. Moreover, the huge progress on the communication systems lead to making the measurements of the signals that were used in our study more easily such as currents, voltages, loads, generations, EVs SoC, and switches status. In addition to the environmental parameters as temperatures, irradiance, wind speed, which are used in the control systems. Moreover, the electricity prices that used with the control of EVs different integration into power system.

The large integration of the RESs and EVs leads to face many challenges such as intermittence power generation, stochastic, and low inertia features, power loss, stability, reliability, etc. Therefore, the different applications of SMES were tested and proposed to overcome the challenges such as VSG application, power-leveling application, power management, and coordination between the SMES, PV, EVs, loads, and wind turbine. Moreover, in the existing power systems that contain different ESSs and some expansions by RESs integrations; the SMES system can be installed to cover the part of the expansions and avoid the RESs operational problems.

6. Directions of Further Research

There are several research points in the topic of application of energy storage in the modern power system that need more investigation. From the limitations of the work are the cost of the SMES system, the fault condition of the power electronic devices, and the temperature of the superconducting state. Emerging problems that come from this research include the following.

- Effect of temperature on superconducting state

During the operation of the SMES system, the superconducting state must be maintained, so the effect of the temperature during various operation modes should be studied and taken into consideration with the controller.

- Hybrid energy storage systems

One of the recent trends of the ESSs is to apply multi-ESSs to achieve the best performance from each one. Moreover, the environmental and economic aspects can be achieved through the hybrid ESSs applications.

- Recent optimization techniques with SMES and EVs

Recent optimization techniques such as slap swarm, moth flame optimization and grey world optimizer can be employed for further optimizing the proposed control methods of SMES and EVs.

- Auxiliary controller with the virtual inertia

The future work related to this point will focus on using an auxiliary controller with the virtual inertia part to reduce the system frequency steady-state error as well as its rate of change. In addition, an auxiliary inertia-damping property of the PV system can be tested.

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