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Simulation studies on ECS application in a clean power distribution system

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ABSTRACT

Dealing with power distribution system became one of the most important arts in the field of power system, especially in the rapid increase of the distributed generation (DG) penetration to the distribution level which is a vital and important part of the entire power system. In this paper, a very special power distribution system with a unique deployment of distributed generation, such as, photovoltaic and wind generation has been studied. Energy storage system is utilized to play the main role to control the system's power quality and the system frequency, as load following operation (LFO) and automatic generation control (AGC), respectively. In this paper, a working criterion has been introduced followed by a case study focuses on two important conditions, one of them when the proposed system is connected to the electrical grid (upper system) and the other one when the system is completely islanded. In both cases, the crucial usage of the ECS gives a concrete result which made the system fully recommended to be applied in real life.

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1. Introduction

Deregulation of electrical utilities, environmental concerns and globalization could be the main reasons behind the rapid increase of using small and clean distributed power sources such as photovoltaic, wind energy, fuel cells and energy capacitor devices. Providing an integrated performance and flexibility of the power system, is an urgent need to be implemented especially in the presence of uncontrollable and environmentally dependant power sources.

Previous studies explained the situation when dealing with distribution systems in the presence of distributed generation [1–4]. Some of them discussed analytically the allocation of distributed generation in primary distribution network [1]. Ghosh et al. used a conventional iterative search technique along with Newton Raphson method of load flow for the optimal sizing and placement of the distributed generation. They claimed that the conventional method is simple with maximum potential benefits [2]. Others achieved to find the optimal allocation for reliability, losses, and voltage improvement [3], and others discussed about the distributed generation contribution to primary frequency control [4]. Ibrahim et al. included the ECS as energy storage in super-capacitors in their comparison study about energy storage system [5]. It is however, the impact of distributed generation makes the system very sensitive to perturbations.

In this paper, the ECS as a new technology of energy saving is proposed to be utilized in power distribution system. Thus, many

other applications of the capacitors and ultra capacitors have been reviewed in order to make the study more comprehensive. Okamura [6] introduced the ECS in a basic study; however, overall characteristics have been discussed. It has been noticed that ECS applications are rapidly increased such as [7–10].

In this paper the control scheme based on the coordination between the ECS and the dg, as controllable devices, has been proposed together with multi-agents and computer network utilization which is widely used application. The influence of the computer network failure has been checked and treated in proper way. PI and PID controllers have been used to solve the problem of ECS size limitation and to complete the coordination process. A long process of parameters and gains tuning has been hold based on trial and error methodology. Yet, further studies in the control strategies are ongoing, such as [11], where intelligent controllers, namely fuzzy logic switching have been utilized.

Medium tension power distribution system is a very important and sensitive part of the total power system. It links the transmission and consumers, it also supplies many industries and other vital parts and utilities. This paper takes one of the most common distribution levels to be studied and to prove the proposed methodology. Unlike many other cases such as in [12,13], this case study and the related simulations have discussed more details of the distributed generation effect. It is somehow similar to [14] in the case of PV units locations. The main two applications related to our scheme are LFO and AGC, where the infinite bus is connected to the target system in the LFO case and disconnected in AGC case. Basically the main objective of LFO is to maintain the power quality received from the upper system as in [15], while the main objective

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Nomenclature

ECS	energy capacitor system
LFO	load following operation
AGC	automatic generation control
PV	photovoltaic
dg	diesel generator
WTG	wind turbine generator
$V_a, V_b,$ and V_c	nominal line voltages
$I_a, I_b,$ and I_c	currents injected to the system
P_e	electrical output of the generator

P_{up}	power from the upper system
P_{ECS}	power from the ECS unit
E_{ECS}	stored energy
P_{dg}	power from the diesel unit
P_{pv}	total output from PV units
P_{wt}	total output from wind turbine
ΔP_{load}	changes in the variable load
$d\omega$	speed deviation

of AGC is to maintain frequency at or very close to the specified nominal value [16]. Khodabakhshian and Hooshmand found a new PID controller to deal with the matter of automatic generation control with a promising result for regulating the frequency [17]. However, their method is focused only on hydro power systems. Bhatt et al. utilized capacitor energy storage to solve the problems of two-area multi-units automatic generation control. According to them capacitor energy storage was not enough to complete the AGC control strategy but they used an additional combined integral-thyristor-controlled phase shifter (TCPS) [18]. In this paper the utilization of the ECS was investigated in a wider range of applications with a unique strategy of utilizing multi-agents and computer networks.

2. System description

The target system of this study is a ring/radial medium tension power distribution system (6.6 kV). It contains several electrical elements including all bus bars and nodes. Electrical machinery and renewable energy sources such as WTG and PV units are deployed at different locations of the system. Also, constant and variable loads are available including ECS as a storage device. PV units are connected at every node of the target system. Different outputs have been considered for every PV source to match with the environmental situation and different locations. Fig. 1 shows the single line diagram of the described system. The mathematical expressions of using the components in the distribution system are expressed by the concept of connecting any device to the distribution network by current injection. In our case the three-phase voltage from the distribution system is used as an input and the output will be the current injected to the system. That model is shown in Fig. 2 and expressed in the set of Eq. (1).

$$V = [v_a \ v_b \ v_c]^T \quad \text{and} \quad I = [i_a \ i_b \ i_c]^T; \quad (1)$$

$$i_a = \frac{K}{1+sT} v_a, \quad i_b = \frac{K}{1+sT} v_b \quad \text{and} \quad i_c = \frac{K}{1+sT} v_c$$

The factor K varies depending on the insolation, random changing signal and power modulation in case of PV systems, variable load and ECS respectively. In case of PV the factor K is always positive ($K > 0$). In case of ECS, the factor K can be controlled to determine the charging/discharging operation of the ECS as if $K > 0$ represents discharging operation and if $K < 0$ represents charging operation. In case of variable Load, the factor K is always negative ($K < 0$). On the other hand wind turbine and diesel generator models have the dynamic model from Matlab/Simulink library with a synchronous generators considered in both the cases.

2.1. WTG model

In the literature, several studies have been reported regarding wind turbines and wind power driven generators [19]. The model proposed in this paper is based on the wind speed versus wind turbine output power characteristics. The power extracted from wind is given by the following equation [19].

$$P_{wt} = \frac{\rho \cdot A}{2} V_{wind}^3 \quad (2)$$

where ρ is air density in kg/m^3 , A is the turbine swept area in m^2 and V_{wind} is the wind speed in m/s .

Mathematical relation for mechanical power extraction from the WTG can be expressed as in Eq. (3) [19].

$$P_e = \eta_m \cdot \eta_g \cdot P_m \quad (3)$$

where λ is the tip speed ratio, β is the blade pitch angle and $C_p(\lambda, \beta)$ is the performance coefficient of the turbine.

Fig. 1. Single line diagram of the distribution system.

The coefficient of performance is not constant, but varies with the tip speed ratio. A generic equation is used to model $C_p(\lambda, \beta)$ as shown in the following equation

$$C_p(\lambda, \beta) = c_1(\beta)\lambda^2 + c_2(\beta)\lambda^3 + c_3(\beta)\lambda^4 \quad (4)$$

This equation, based on the wind turbine characteristics and the coefficients c_1 , c_2 and c_3 are determined according to Simulink model of the wind turbine which has been modified in Power System Laboratories of Kumamoto University, Japan. The tip speed ratio can be obtained from Eq. (5).

$$\lambda = \frac{R \cdot \omega}{V_{\text{wind}}} \quad (5)$$

where R is radius of the wind turbine and ω is the wind turbine rotation speed. The electrical power generated by the WTG was defined as in Eq. (6) [20].

$$P_e = \eta_m \cdot \eta_g \cdot P_m \quad (6)$$

where η_m is the mechanical efficiency and η_g is the generator efficiency.

Fig. 3 illustrates the Simulink block diagram of the wind turbine model and Fig. 4 shows the total power output from the wind turbine generator.

Fig. 2. Mathematical expression of the connected models.

Fig. 3. Simulink model of the WTG.

Fig. 4. Output power of the WTG.

2.2. PV system model

Mathematical model of the PV system has been made in the AC side of the units for the sake of simplicity. In this paper, the three-phase instantaneous model used and the fluctuations in electric power caused by the PV system are enough to be represented in the AC side of the photovoltaic units. The insolation has been modeled in Matlab/Simulink together with the gain and the time delay. The mathematical model represents the complete three-phase instantaneous model of the PV unit. The input is the three-phase voltage and the output is the three-phase current which is injected to the network. The power can be calculated by multiplying the voltage and current. The connection method of the PV unit to the distribution system is illustrated in Fig. 5. In this paper the photovoltaic units are placed at every node of the target system to check their impact on the distribution system of several environmental conditions, and several location conditions, therefore the output power delivered from those units appears as shown in Fig. 6.

2.3. ECS model

Energy capacitor system (ECS) consists of capacitors and power electronics. It is used as an energy storage system. The capacitor part of the ECS is a group of electric double layer capacitors of increased energy density. Similar to PV and other elements, the AC side of the three-phase instantaneous model is considered in this paper. Charging and discharging operation of the ECS is utilized for LFO control and for AGC as well. Fig. 7 shows the charging and discharging operation concept with the limitations of having fully charged or fully discharged conditions. Keeping the charging/discharging operation in the specified range vitally depends on the dg support and using the suitable controllers. The charging and discharging level of the ECS was specified from 0.9 kW h to 3 kW h in the case study of this paper. Fig. 8 illustrates the way of connecting the ECS to the distribution system.

Fig. 5. Matlab/Simulink diagram of connecting the PV model to the system.

Fig. 6. Output power of the PV units.

2.4. dg model

From an electrical system point of view, a diesel generator can be represented as a prime mover and generator. Ideally, the prime mover has the capability to supply any power demand up to rated power at constant frequency. The synchronous generator connected to it must be able to keep the voltage constant at any load condition. The diesel engine kept the frequency constant by maintaining the rotor speed. When power demand fluctuates the diesel generator could vary its output via fuel regulation to its governor. The synchronous generator must control its output voltage by controlling the excitation current. Thus, the diesel generating system, as a unit, must be able to control its frequency and its output voltage. The ability of the diesel generator to respond to frequency changes was affected by the inertia of the diesel gen-set, the

sensitivity of the governor, and the power capability of the diesel engine. The ability of the synchronous generator to control its voltage was affected by the field-winding time constant, the availability of the DC power to supply the field winding, and the response of voltage control regulation [21]. The Matlab/Simulink block diagram of the synchronous generator together with the optional governing system is shown in Fig. 9, where P_m is the Mechanical power at the machine's shaft and V_f is the field voltage.

2.5. Distribution lines and fixed load models

Using Matlab/Simulink and namely SimPower Systems from the Simulink library taking into account the three-phase instantaneous-value based model, the line model that presents a three-phase, 4-wire system overhead medium tension distribution lines

Fig. 7. Charging/discharging operation of the ECS with the dg support.

and the three-phase parallel RL load have been used to represent the lines and the constant load respectively.

2.6. Variable load model

The fixed load connected to the distribution system is not enough to represent the real case. Although the fluctuations in power caused by the photovoltaic units and the wind turbine are enough to cause the perturbations on the distribution system, a variable load has been added and simulated to the target system to make it more realistic. Random changes in the variable load have been considered in this paper and shown in Fig. 10.

3. Working criteria

As the system is connected infinite bus and because of the renewable energy sources that scattered around, the big concern is about keeping the power delivered from the upper system as much as regulated as possible, and as small as possible. It should be regulated, to satisfy the consumer's demand of good quality of power. It should be small, to satisfy the need of making the system more independent. In the other hand, after isolating the target system from the upper one, the big concern is about regulating the frequency which is completely influenced by the unbalance between generation and demand. Respectively, LFO and AGC are implemented according to the described criteria.

3.1. Load following operation (LFO)

Multi-agents based load LFO of two levels, global and local, are performed to keep the real power supplied from the upper system regulated with good quality. The multi-agents system is a

Fig. 8. Matlab/Simulink diagram of connecting the ECS model to the system.

Fig. 9. Matlab block diagram configuration of the dg.

Fig. 10. Changes in the variable load.

computer network consists of several personal computers called agents, are responsible about sending and receiving data among each others to perform the control strategy and provide the coordination scheme between elements of the system, namely the ECS and the *dg*. Those agents are divided into three parts:

1. **Monitoring agent** has the mission of measuring the data required from one part of the system and supply it through the computer network to the supervisor agent.
2. Supervisor agent plays the mission of coordination among the controllable devices in the system. It is obviously provided with the suitable algorithm and control strategy in order to send the required data to the control agent.
3. Control agent has the mission of applying the control signal to the desired equipment. The *dg* will operate according to the control value to support the ECS which is small in size but fast in charging and discharging.

Fig. 11 shows the utilization of multi-agents and computer network, where the data files X and Y prepared at the monitoring agent (PC1) have been sent to the hard drives F and G of PC2 and PC3 respectively (PC2 is the supervisor agent and PC3 is the control agent). After that, PC2 inputs the data X received from PC1 and prepares the data file Z to be sent to PC3. PC3 reads the data file Z and prepare the control action. Analogue to digital convertor A/D and digital to analogue converter D/A including Digital signal processing board DSP are used to perform the multi-agent based control action.

3.1.1. Global control

Global control or upper level control is performed when network agents are available and able to coordinate between the ECS and the *dg* which is controllable device and can be easily cover the changes in the demand and the fluctuations in power caused by the wind turbine and the photovoltaic system. In case of the

global control the *dg* receives the required signal from the ECS through the agents to absorb the fluctuations. The ECS itself has a unique characteristic and can easily compensate any power generation lack or absorb any higher generation through the fast charging and discharging operation, but the limited size of the ECS compelled us to keep the charging and discharging level in a certain desired value for technical reasons, that restriction can be avoided by getting the support of the *dg* to the ECS, again through the computer network. Fig. 12 shows the general configuration of the global control. The PI controller used on the ECS side is shown in Fig. 13. The coordination process between the ECS and the *dg* is implemented by the controller shown in Fig. 14.

3.1.2. Local control

This case happens when the computer network fails down due to any reason, in other words, the *dg* and the ECS system are not coordinated during this period of time i.e. working separately. The performance of the energy capacitor system is clearly degraded and the *dg* cannot perform the LFO itself, another technique has been used in this case which is modifying the target power to a certain accepted value to improve the performance of the ECS. The local information in the location of the ECS has been implemented. That is called the lower or local control. Fig. 15 shows the general configuration of the local control. The target power has been modified as the coordination between the energy capacitor system and the *dg* is not possible. Hence, local information taken from the physical bus bar where the ECS is located is used to improve the performance of the ECS, in other words to keep the ECS in the certain charging and discharging level, not to exceed the top charging level and not to come below the minimum discharging level, thus the target power has been modified.

3.2. Automatic generation control (AGC)

Intended islanding of the electrical power distribution system requires high techniques and big caution to control the frequency

Fig. 11. Utilization of multi-agents and computer network.

Fig. 12. Global control configuration.

Fig. 13. The representation of the PI controllers on the ECS.

Fig. 14. The representation of the coordination PI controller.

Fig. 15. Local control configuration.

of the entire system, where the upper electrical system that is responsible about holding the frequency, is absent. This situation has been analyzed after the previous situation of LFO control, done and completed before isolating the system. The well known AGC is presented in this paper to maintain the frequency of the islanded system. Although environmental dependent renewable energy sources, such as grid-connected photovoltaic systems are present and spread within the target system, the frequency deviation can be controlled and minimized by the proposed AGC technique used in this paper. The target system in this part is the same ring/radial distribution 6.6 kV, 60 Hz system with a circuit breaker at the main substation is open. Such a system is common in some special areas like airports and other isolated islands. It is also required to open the main circuit breaker in order to prevent any disturbance in the upper system from being transferred to the target system.

The ECS, which has fast charging and discharging capabilities plays the main role of AGC actively by providing the generation and demand balance condition. Coordination between one of the controllable generation units which is *dg* in this case and between the ECS is implemented to keep the ECS system in the desired charging and discharging level. Multi-agents system and computer networks are also utilized when the *dg* and the ECS are not in the same location, to complete the coordination process.

4. Case study

The Line parameters (resistance and reactance) have been considered for the specified system which is over head, three-phase four-wire system. The active and reactive power are injected to the system in order to match with real situation and more practical

Table 1

Distribution system constants (10 MVA base).

Line no.	Bus bar–bus bar	R	X	PL	QL
1	Substation	1	0		
2	1	2	0.003145	0.075207	0.022
3	2	3	0.00033	0.001849	0.070
4	3	4	0.006667	0.030808	0.170
5	4	5	0.005785	0.014949	0.042
6	5	6	0.014141	0.036547	0.011
7	3	7	0.011472	0.352962	0.022
8	4	8	0.036665	0.169397	0.080
9	6	1	0.01254	0.1257	

Table 2

Initial settings of the distribution system elements.

Element	Initial setting	Maximum value
ECS capacity	1.5 kW h	3 kW h
<i>dg</i>	0 kW	5000 kW
WTG	0 kW	1000 kW
PV at node 2	0 kW	150 kW
PV at node 3	0 kW	200 kW
PV at node 4	0 kW	100 kW
PV at node 5	0 kW	50 kW
PV at node 6	0 kW	400 kW
PV at node 7	0 kW	100 kW
PV at node 8	0 kW	100 kW

cases in cities and household areas. Table 1 shows the 6.6 kV power distribution system constants (10 MVA base) for the Fig. 1. Table 2 shows the initial settings of each distribution system elements. (All models have been discussed in the previous items.)

5. Simulation results

Matlab general representation of the distribution system including all elements in three-phase instantaneous format is shown in Fig. 16. The simulation results following the working criteria illustrated below.

5.1. LFO results

Based on trial and error methodology, the parameters of the PI controllers used at different stages of the control scheme have been tuned until the optimum values obtained to achieve the desired result. Table 3 exposes the tuned parameters. Different strategies to control the real power of the target system have been considered. Figs. 17–19 illustrate the results according to those strategies. In a comparison between the three figures, from the first one the ECS is not in service and no control action is performed which results in a very fluctuated and distorted power delivery from the upper system. Next figure illustrates the coordination control condition where both the *dg* and the ECS are coordinated with each others, which results in a high level of regulation in the real power. The last figure shows the local control where the *dg* is not supporting the ECS due to computer network failure (the computer network is shown in Fig. 11). The power from the upper system has been modified in this case to maintain the saved energy of the ECS in the required specified level.

The evaluation index is expressed in Eq. (6) where the averaged power is calculated to investigate the power deviation from the upper system of the described distribution network and to evaluate the LFO scheme for the different strategies [22].

$$\text{Index} = \frac{\sum |P_{up} - P_t|}{N} \quad (7)$$

where P_{up} is the power from the upper system, P_t the target power, and N is the number of entered data. The obtained indices according

Fig. 16. Three-phase instantaneous-value based model of the target system.

Table 3
Controller tuned parameters in case of LFO.

Strategy	Parameters	On the ECS	On the dg	Coordination controller
Global control parameters	P	0.25	6	0.0125
	I	1000	0.1	0.00005
	Gain	1	0.001	–
Local control parameters	P	0.25	6	0.0125
	I	1000	0.1	0.00005
	Gain	0.005	0.001	–

to the different control strategy are shown in Table 4. Where, the smaller index the better result, as shown in this table. The index is 1.587 kW, under global control strategy.

Other cases have been performed and digitally simulated when computer network fails down and then recovers after a certain time, as shown in Fig. 20 which illustrates a condition when the computer network and the Multi-agent system failed down due to some reason. At the beginning the global control is activated and the real power received from the upper system is quit regulated, at the time 20 s, the computer network failed down and the control strategy is switched to a local controller with target power modification according to the block diagram in Fig 15. At 60 s the computer network recovered, the ECS started compensating the lack of generation in this case through discharging process and the dg started supporting the ECS directly after detecting the energy level of the ECS which is approaching a critical discharging level. That is exactly as explained by Fig. 7.

Fig. 17. LFO results under no control action.

Fig. 18. LFO results under global control action.

Fig. 19. LFO results under local control action.

Table 4
LFO indices for different control strategy.

Control strategy	Index
No control	232.498
Global control	1.587
Local control	137.711

5.2. AGC results

After isolating the system, PID controller utilized to control the system where trial and error base parameters tuning has been

performed as shown in Table 5. As shown in the AGC results illustrated in Figs. 21–23 and by suitable evaluation index. It is quite clear that response of the ECS to the unbalanced situation between generation and demand caused by renewable energy sources is very fast. Also, the main reason of this situation is the islanding process. Fig. 21 illustrates the conventional case where ECS is not used. That results in a speed deviation to be out of synchronization where the dg has no enough capabilities to overcome the problem. Fig. 22 shows the governor action as a classical method used to regulate the frequency. Fig. 23 shows the implantation of the ECS which results in very small changes in the system's frequency

Fig. 20. LFO results under global-local-global control condition.

Table 5
Controller tuned parameters in case of AGC.

Parameters	On the ECS	On the dg	Coordination controller
P	100	6	0.0125
I	2	0.1	0.00005
D	1	–	–
Gain	–10,000	0.001	–

represented by the speed deviation in this paper. However, it is clear that in the first 10 s the dg was not able to control the frequency unless the ECS activated. Once ECS operates, the dg is not obligated to absorb the fluctuations as the ECS does so. To evaluate the result, an index expressed by the mean value of the speed

deviation is used. The evaluation index is shown in the following Eq. (7) [23].

$$\text{Index} = \frac{\sum d\omega}{N} \quad (8)$$

where $d\omega$ is the speed deviation taken at the dg side and N is the number of the taken data. Table 6 shows the obtained indices of different scenarios and it can be clearly seen from the table that utilizing the ECS gave the best result which is 0.0028 rad/s.

6. Conclusion

Ring/radial distribution system which can be reconfigured into different types of radial systems is very reliable and flexible and does not affect the control scheme process in the presence of

Fig. 21. AGC results under conventional condition.

Fig. 22. AGC results by using the Governor.

Fig. 23. AGC results by using the ECS.

Table 6

AGC indices for the different scenarios.

Scenario	Speed deviation (rad/s)		
	Max	Min	Mean
ECS OFF, governor OFF	1.913	0.42	1.38
ECS ON, governor OFF (only ECS)	0.037	−0.0061	0.0028
ECS OFF, governor ON (only Governor)	0.038	−0.024	0.0082

dispersed power sources. Such a system has been put under research in this paper with analogue and digital simulations. Applying the suitable controller under the mentioned working criteria of different scenarios and strategies led to the following conclusions.

1. Multi-agent based LFO control is a useful scheme used to regulate the power supplying a distribution system of about 5 MW load.
2. The hierarchical control scheme is applied on two levels of control, high or global level and lower or local level, which is a necessary way to be used in order to solve the problems of computer network complexities.
3. AS ECS plays the main role in the control scheme with the minimum size has shown a very good response of absorbing the fluctuations. For a zero fluctuations as a target value, the improvements are 232.5 kW without ECS to 1.6 kW with ECS.
4. Local control in the case of computer network failure is also possible and the obtained results are better compared with the case if the ECS is not present. As for a modified target value of real power fluctuations, the improvements are 232.5 kW without ECS to 138 kW with ECS.
5. Comparing the simulation results, it has been noticed that, the efficient usage of the ECS to complete the process of AGC in order to keep the speed deviation measured at the generator side constant, which results in a constant frequency of the

system. In other words 0.0028 as a mean changes in the speed deviation is quite accepted compared with 1.38 which is not accepted range of speed deviation.

6. Although the governor has been tested to play the same role, results show more efficient usage of the ECS in addition to the time delay which may occur due to the action of the governor (in Table 6, $0.0028 < 0.0082$).
7. The ECS compared with the governor is more capable to implement AGC for an isolated distribution system which can be safely islanded in the presence of renewable energy sources without any worries about the frequency of the system while ECS is present. Furthermore, in case of any fault might occur in the large scale system, the proposed scheme will keep the target system in the safe side.

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