Microgrid Stability Enhancement by using Coordination of SFCL, SMES and Distributed Generation Units with Fuzzy Logic Controller

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Abstract: By the coordination of the superconducting fault current limiter (SFCL), superconducting magnetic energy storage (SMES) and distributed generation (DG) units, the stability of the microgrid is increased under short circuit fault conditions. And by this coordination control, the microgrid is smoothly separated from the main network under severe fault and attains a fault ride through (FRT) operation under minor fault. In this paper, to overcome the drawbacks of the PI controller a fuzzy logic controller (FLC) is used in the controller of the SFCL. This proposed method is carried out in a MATLAB/Simulink. The results show the achievement of a better control strategy.

Index Terms: Coordination Control, DG units, FLC, Microgrid, SFCL, SMES.

I. INTRODUCTION

Because of the continuous increasing nature of the power exchanges and penetration levels, it is difficult to obtain the stability of a microgrid under short circuit (SC) fault conditions. In case of a permanent fault, there are some vital challenges to transfer the microgrid to an island operation from the main grid operation like a comparatively low system inertia in managing the power unbalance. Therefore, an efficient frequency and voltage regulation is necessary to operate the microgrid in an island mode, otherwise, the voltage and frequency deviations within the microgrid will increase the power unbalance by reaching out of tolerance range.

In regards to this issue, superconducting power devices are introduced in electrical power system, which have great potentials in increasing the stability of power system [1]. SMES and SFCL are the two representatives, which may be exploited not solely in high-voltage main-grids however additionally in low-voltage microgrids [2],[3], typically designed to integrate and maximize the use of DG units.

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By the introduction of SFCL to the microgrid, fault current is reduced and the voltage sag is mitigated when the microgrid is undergoing mode transfer, the fault current surge is reduced and also the microgrid voltage recovery method is accelerated at the instant of island mode is achieved. In addition, by using a SMES in the microgrid it provides a subsequent active and reactive power compensation and also provides voltage and frequency references to maintain stable operation of the microgrid
From this point of view, advantages of both the devices SMES and SFCL can be combined to provide better microgrid control capability. Fuzzy management has transpired as the foremost active and fruitful analysis area, due to lack of quantitative input and output data for conventional methods. If this management relies on fuzzy logic, then the system is far nearer to human thinking and linguistic communication than ancient language [4]. FLC supported fuzzy logic, gives a way to turn an expert knowledge-based linguistic management strategy into an automatic management strategy.

In view of the literature survey, the selection of a SFCL and SMES has been receiving more and more attention. In [5]-[7] the combined usage of SMES and SFCL are studied, but few details are related to microgrid. Nevertheless, when using a flux coupling type SFCL and a SMES system the transient performance under fault conditions is improved [8]. Currently, coordinated control of the regular (conventional) and superconducting power devices has been used to increase the stability of the microgrid under short circuit faults [9]. Despite the fact that this specialized thought has been demonstrated accomplishable the regular controller has few drawbacks.

In this paper, a coordinated control of an active SFCL, SMES and the DG units with a fuzzy logic controller is proposed for a microgrid, and it is anticipated to increase the steadiness of a microgrid when a short circuit fault is occurred. Here, a conventional PI controller is replaced with the FLC in the controller of a voltage compensation type active SFCL and the difference of fault severities are investigated.

II. THEORITICAL ANALYSIS

A. Modelling and Control of the SMES

SMES can offer several technical advantages when compared with the other energy storage devices such as quick response, high efficiency, high energy density, and a very high cycling capacity over short period of time.

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And also offers great controllability to constant power flow, frequency and voltage, when the SMES is introduced to a microgrid. A typical SMES system includes three parts: superconducting magnetic coil, a dc-chopper and a voltage source converter.

The mathematical model of voltage source converter is expressed as:

$$L\frac{di_d}{dt} = e_d + \omega L i_q - v_{dc}s_d \qquad (1)$$

$$L\frac{di_q}{dt} = e_q - \omega L i_d - v_{dc}s_q \qquad (2)$$

Where,

L   connecting inductance
i, e   current and voltage
d, q   d and q axis
v_{dc} voltage over the converter's DC side
s   control signal

The current control equation is expressed as:

$$v_{vsc_{d_{ref}}} = \left(K_p + \frac{K_i}{s}\right)\left(i_{d_{ref}} - i_d\right) + e_d - \omega L i_q \qquad (3)$$

$$v_{vsc\_q_{ref}} = \left(K_p + \frac{K_i}{s}\right)\left(i_{q_{ref}} - i_q\right) + \omega L i_d \qquad (4)$$
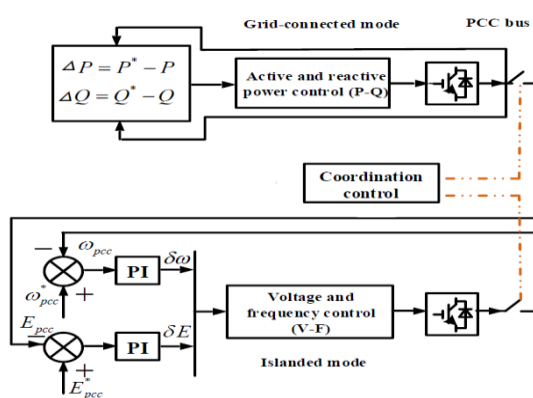

Fig 1. Control Block diagram of the SMES.

Fig 1 demonstrates the control square outline for the SMES. The SMES works in an active and reactive power control (P-Q control) when the microgrid is associated with the main network, to attain an anticipated power output [10]. Furthermore, it works in voltage and frequency control (V-F control) when the microgrid connects to the island mode, to stabilize the microgrid. The coordinated control center manages the control action between P-Q and V-F modes.
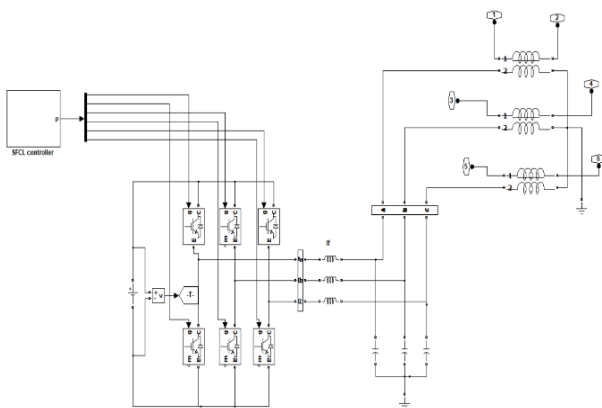

Fig 2. Simulink model of a voltage compensation type active SFCL.

B. Modelling and Control of an Active SFCL

As demonstrated in Fig 2 an active SFCL is comprised of 3 main parts, an air-core superconducting transformer, LC filter and a voltage source converter with Pulse-Width-Modulation (PWM). The working principle of an active SFCL is, under normal state the current in the secondary side of the air-core transformer is managed to a value that makes the Z_{SFCL} to zero so that there will not be any effect to the main circuit by an active SFCL [11]. And when the fault is occurred, the injected current is adjusted to regulate the series compensation voltage and reduce the fault current as it raises from I_1 to I_{1f}.

$$\dot{I}_{1f} = \frac{\dot{V}_s + j\omega M_s \dot{I}_2}{Z_1 + j\omega L_{s1}} \qquad (5)$$

$$\dot{V}_{1f} = j\omega L_{s1}\dot{I}_{1f} - j\omega M_s \dot{I}_2$$

$$= \frac{\dot{V}_s(j\omega L_{s1}) + \dot{I}_2 Z_1(j\omega M_S)}{Z_1 + j\omega L_{s1}} \qquad (6)$$

The current restricting impedance can be managed as

$$Z_{SFCL} = \frac{\dot{V}_{1f}}{\dot{I}_{1f}} = j\omega L_{s1} - \frac{j\omega M_s \dot{I}_2(Z_1 + j\omega L_{s1})}{\dot{V}_s + j\omega M_s \dot{I}_2} \qquad (7)$$

Based upon the regulating current of I_2 there are three operating modes:

1) The regulating current I_2 is made to exist in the actual state

     $Z_{SFCL-1} = Z_1(j\omega L_{s1})/(Z_1 + Z_2 + j\omega L_{s1})$.

2) Managing I_2 to zero, $Z_{SFCL-2} = j\omega L_{s1}$.

3) The phase angle of I_2 is regulated such that the difference in the angle between $\dot{V}_s$ and $j\omega M_s \dot{I}_2$ be 180°, $Z_{SFCL-3} = cZ_1/(1-c) + j\omega L_{s1}/(1-c)$ is obtained.

From the above three operating modes, the coordinated control center will select one mode and send it to the converter controller of the SFCL.
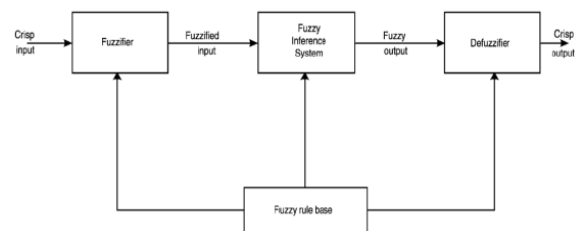
Fuzzy Logic Controller (FLC):

Fig 3. A Simple Fuzzy Logic system

FLC is used in the controller of a SFCL before sending the signal to the PWM module. It has been outstanding in dealing with complex, undefined, non-linear or time-varying systems. It is comparatively simple to execute because the control system usually does not need a mathematical model. It is a mathematical tool for managing vulnerability. Fuzzy logic systems have quick and smooth response when compared with conventional systems and have less control complexity [4].
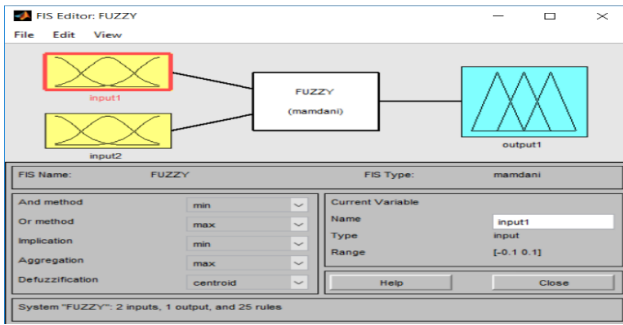
Fig 4. Fuzzy Inference Structure (FIS) editor showing number of inputs and outputs for Fuzzy Logic Controller.

A basic fuzzy framework consists of four blocks as shown in the Fig 3, A Fuzzifier, Inference Engine, Defuzzifier and Fuzzy Rule Knowledge Base. FLC is an appealing selection when accurate mathematical formulations are not doable.

A Fuzzy set is described by a function that maps objects to their membership value in the set, in the domain of concern. Such function is referred to as a membership function.
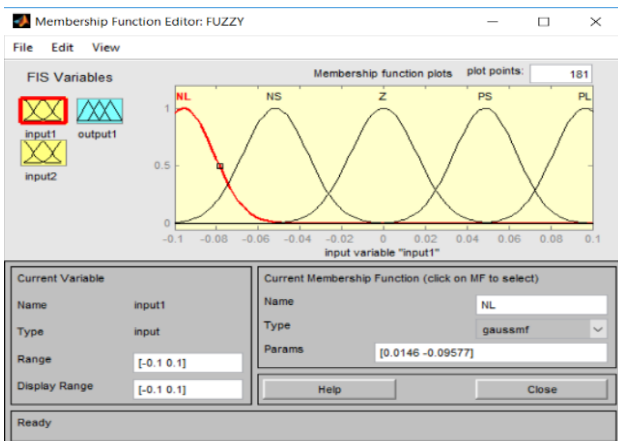

Fig 5. Membership function editor for 2 input's whose MF is Gaussian and 1 output whose MF is Triangular.

Fig 4 demonstrates the selection of input's and output's in the form of Membership Function so as to design FIS. Therefore, it looks like the choice of two input's and one output. Fig 5 demonstrates the Fuzzy membership function editor, where the number of membership functions and their type is selected according to the process parameter like Gaussian, Trapezoidal and Triangular. Fuzzification is nothing but the fuzzy logic operation. Mostly triangular shape is used for the calculation to be moderately basic. Fuzzy rule base has if-then statements, where the fuzzy control rule depends on fuzzy decision making, which meets certain information conditions and results in a yield. Here, the benefits of a fuzzy based controller over conventional PI controller are observed from the outcomes.

The active SFCL gives the accompanying performance benefits: 1) Because of the converter, there will be high controllability and flexibility. 2)High relevance due to transformer adjustment for different voltage levels. 3) Excellent Z_{SFCL} linearity due to avoiding air-core magnetic saturation. And as there will be no iron loss in the air core superconducting transformer, there will be reduction in size, weight and hormonic when compared with conventional

iron core superconducting transformer [12]. To sum up, the introduction of the active SFCL in the microgrid offers a sensible potential to respond to the control commands and to participate in the coordinated operation.

It ought to be noticed that the Active SFCL with a Fuzzy Logic Controller is better in suppressing the fault current and compensating the voltage sag before the microgrid is divided from the PCC, when compared with the active SFCL with conventional PI controller.
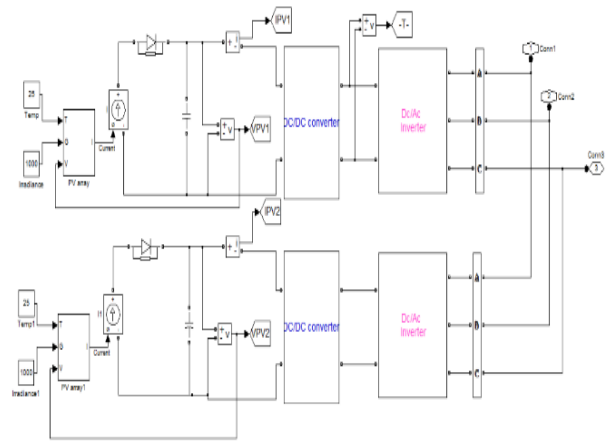

Fig 6. The layout of a PV generation unit connected to the microgrid.

C. Configuration and Control of the PV unit

As shown in Fig 6 there are 2 PV units connected in parallel. Each unit has boost-converter and an inverter. In normal condition, MPPT technique control will be adopted by the Boost-Converter to make certain PV efficiency. For each unit the power equation can be written as:

$$P_{PV} = P_{C1} + P_g \qquad (8)$$

where P_{C1} is the stored power in the DC-link capacitor C_1 of first PV unit, P_g is the output from the inverter, P_{PV} is the output of the PV array. If the loss of the converter is disregarded, then $P_{PV} = P_g = 3V_{ph}I_{ph}$, where I_{ph} & V_{ph} are rms values of phase current and phase voltage respectively. At the point when the fault is occurred, the PCC's sudden voltage drop will reduce P_g to P_{gf} power output and in the mean-time, the DC/DC unit keeps on infusing the maximum power possible into DC-link capacitor.

The equation at the DC-link capacitor will be given as [13],

$$(P_{PV} - P_{gf})\Delta t = P_{C1}\Delta t = \frac{1}{2}C_1(V_{C1-f}^2 - V_{C1}^2) \qquad (9)$$

where V_{C1} & V_{C1-f} are the voltages at the DC-link capacitor before and after the fault and Δt is the time frame of fault.
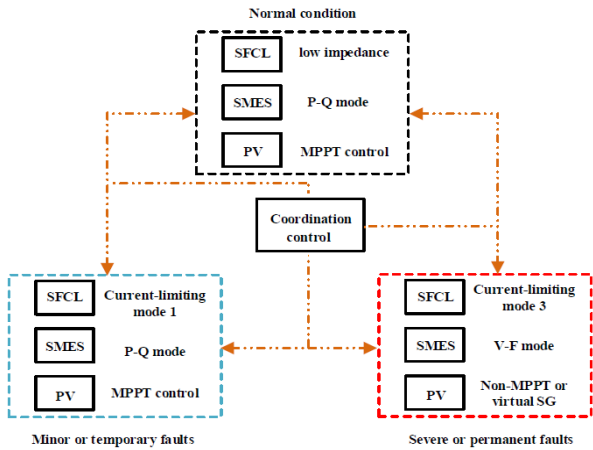
Fig 7. Fundamental principles of the switching control under various operating conditions. Note: virtual SG denotes Virtual Synchronous Generator.

From (9), V_{C1-f} can be derived as

$$V_{C1-f} = \sqrt{\frac{2P_{PV}\mu\Delta t}{C1} + V_{C1}^2} \qquad (10)$$

where $\mu = \frac{V_{ph}-V_f}{V_{ph}}$ here μ indicates the voltage drop depth and V_f is rms value of the phase voltage at the time of fault condition. From (10), as μ & Δt increases, the voltage at the DC-link will increase to a large value. To avoid this, MPPT control is disabled and the reduction in the power P_{PV} will help to avoid the capacitance damage and to reduce the power imbalance. Furthermore, the PV Voltage Source Inverter (VSI) can offer reactive current support based on various levels of dropped voltage. Therefore, the reference equations of the Active Power P_r and Reactive Power Q_r are given as

$$P_r=3V_gI_{dpv-r} \qquad (11)$$
$$Q_r=3V_gI_{qpv-r} \qquad (12)$$

where I_{dpv-r} & I_{qpv-r} are the references for the active and reactive current. Which can be calculated as given in [13].

D. The basic principles for the coordination of the SMES, an active SFCL & the PV unit

The basic coordination principles of the control switching under various operating conditions are given as: The balanced power of the microgrid in the normal condition is

$$P_{PV1}+P_{PV2}+P_{SMES}=P_{load1}+P_{load2}+P_{ex}$$

(13) where P_{ex} is the power exchange between microgrid and main network. The power loss is neglected, since the active SFCL has low impedance.

If a fault occurs, there will be reduction in PCC voltage sag which will decrease the load power & power exchange and are denoted as $P_{load1-f}$, $P_{load2-f}$ & P_{ex-f} respectively. By the activation of SFCL, the PCC voltage drop is mitigated due to which there will be increase in power load & power exchange, and are marked as $P'_{load1-f}$, $P'_{load2-f}$ & P'_{ex-f} respectively. Furthermore, an active SFCL will dissipate the excess power from the micro-grid to the main-grid and this is represented by P_{SFCL}. Under the fault condition the power equation of the microgrid is re-written as

$$P_{PV1} + P_{PV2} + P_{SMES} = P_{SFCL} + P'_{load1-f} + P'_{load2-f} + P'_{ex-f}$$

As

$$P_{SFCL} + P'_{load1-f} + P'_{load2-f} + P'_{ex-f}$$
$$> P_{load1-f} + P_{load2-f} + P_{ex-f}$$

The pressure on the SMES and the DG units can be reduced by the presence of the active SFCL to manage the power unbalance.

If a temporary or minor fault occurs, the coordination is intended to help the microgrid to perform a Fault Ride Through (FRT) operation in order to strengthen the power supply when the voltage sag is at a suitable level.

The coordination center will make the active SFCL to operate in current-restricting mode1 and the SMES in the original P-Q control in view of determination of fault severity and let the DG unit retain the MPPT control. The coordination control allows to ensure microgrid transient stability by means of this smooth control of the SMES, SFCL & DG units, as the fluctuations from the voltage and current may have certain limitations under minor or temporary faults.

If a severe or permanent fault occurs, the microgrid is to be separated from the main grid, since it can lose the possibility of providing stable power exchange with severe voltage dips, and the coordination must ensure a secure and reliable separation of the microgrid. As per the specified types of fault the coordination center will actuate the SMES to switch between its V-F control & P-Q control and make the active SFCL to work under current-restricting mode 3 and to allow the DG units to participate in regulating the voltage-frequency. Because of the dispatchable dispersed source of many DG units, they can use virtual SG technology or modify their initial power tracking modes to take part in stability control [14].

In a way, a heuristic approach is the basis of the proposed coordination control, However, systematic consideration is given to cooperation between the SMES, an Active SFCL & the DG unit. Even, static power loads can therefore be seen to be involved in the adjustment of power, since the voltage on it is remunerated by SFCL. Indeed, irrespective of major or minor faults SMES, SFCL & DG units will be coordinated in a transient process. If there is an occurrence of major fault, the transient process denotes the duration of time after the fault & before the separation of microgrid and the transient process for minor fault indicates the time interval of the fault.

In view of the above description, Fig 7 demonstrates the fundamental principles of control switching under various operating conditions.
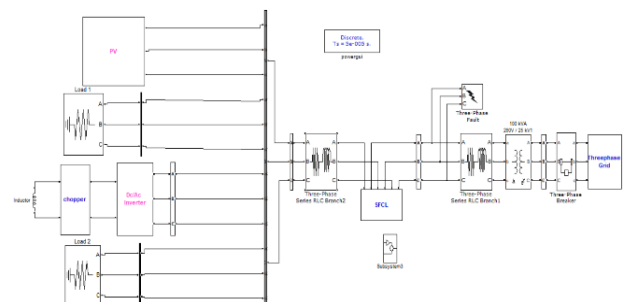

Fig 8. Simulink model of a microgrid with SMES, SFCL and DG Units.

III. SIMULATION STUDY

A. System Modelling

Fig 8 shows the simulation diagram of the microgrid with the coordination of SFCL, SMES and DG units. The simulation parameters of this model are given in Table-I.

TABLE I
Simulation Parameters of the model

Microgrid with SMES, an Active SFCL & DG Units	
PV_1/PV_2	50 kW / 80kW
Power Line	$0.27+j0.347\Omega$/km, 2 km
Nominal Load ½	60 kW / 40 kW
Nominal Voltage/Frequency	10 kV / 50 Hz
SMES Magnet	150 kJ / 100 kW
SMES Chopper	800V/ 5000 μF
Active SFCL	L_{s1}=80mH,$_{s2}$=80mH,M_s=72mH

The PV unit is modelled based on reference [15]. Under normal state the two PV units uses P-Q control and attains a maximum output. And in case of a permanent or severe fault, Non-MPPT technique is adopted for protection and assists in power regulation.

Resistor element based static power load is taken in the analysis of simulation and the equation of power can be expressed as $P_{load}=3V^2/R$, where V is the resistor phase voltage and R is the value of resistance.

In the SMES modelling, the standard models of chopper and the voltage source converter are used from the library of MATLAB and the superconducting magnetic coil is indicated by a non resistive inductance model [16].

For the SFCL modelling, a voltage source converter combined with a DC capacitor is built for the converter and an air core superconducting transformer is represented by a non resistive transformer. For the choice of the SMES and SFCL specifications can basically refer to [17].
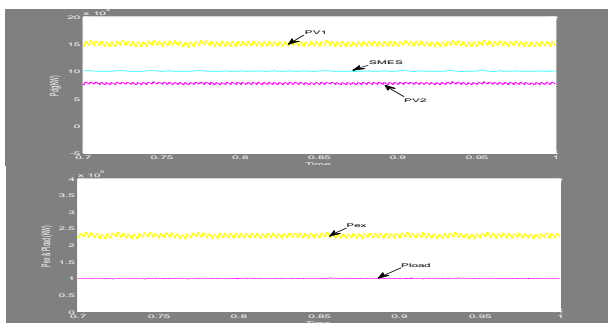

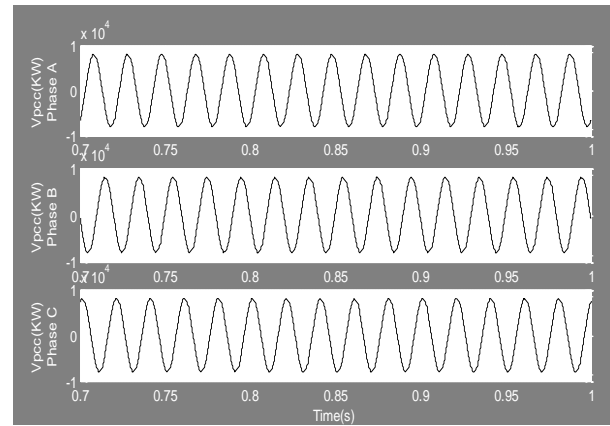**Fig 9. Operation behaviour of the microgrid in normal condition.**

Fig 10. Three-phase PCC voltage of the microgrid in normal condition.

B. Normal condition simulation

Fig 9-10 shows simulation results of DG Power P_{DG}, Exchange Power P_{ex}, Load Power P_{load} & three phase PCC voltage when the microgrid system is operating in its normal energy exchange state. In the case of normal condition, the SFCL has no effect on microgrid operation and the SMES is able to maintain exchange capacity at the 250KW level. As the DG unit output is greater than that of two local power loads, the exchange power flow direction is from microgrid to the main network. The external properties of a microgrid are equivalent to a power source that is well supported by voltage and frequency of the main-grid.
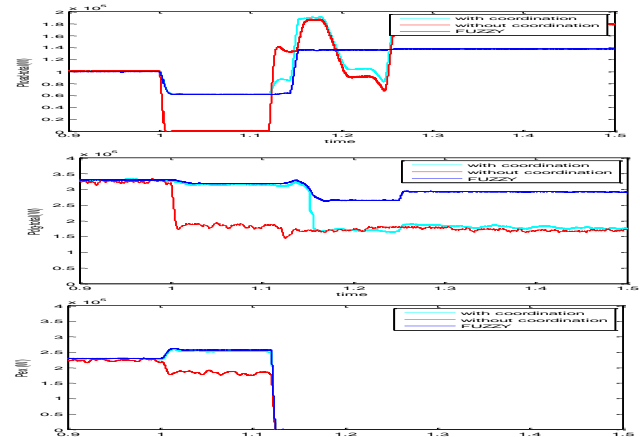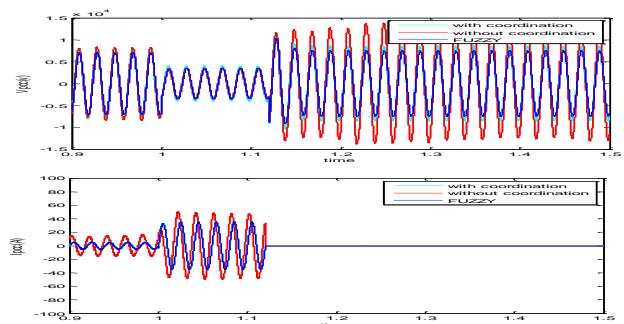

Fig 11. Power curves of the microgrid under severe fault. (a) Load power Pload, (b) Total DG power PDG-Total. and (c) Power Exchange Pex.
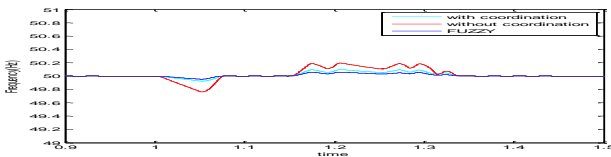
Fig 12. Operation behaviours of the microgrid under severe or permanent fault. (A) PCC voltage, (B) PCC current and (C) Frequency response.

C. Severe fault simulation

To describe a permanent fault, a three phase short circuit fault is created nearer to the main-grid at t=1sec and the fault resistance is taken as R_g=0.5Ω. After the fault, the switch at the PCC will be opened at 120ms and the microgrid will then operate in its islanded state. Fig 11-12 shows comparison of the transient behaviour of the microgrid without and with coordination control and also with fuzzy control.

By the illustrated figures, the coordination control of an Active SFCL, the SMES & the DG unit serves the following contributions. 1) The load recovery is accelerated and the power balance is maintained. 2) The PCC voltage sag is compensated and the PCC fault current is suppressed. Improving the power quality and reducing the frequency fluctuation.

When this coordination control is operated with FLC then there will be an improvement in the result, such as reducing the frequency fluctuations, maintaining the PCC voltage to a constant value, reducing the fault current and a new balancing power for the stable operation is accomplished earlier when the microgrid is operating under island mode.
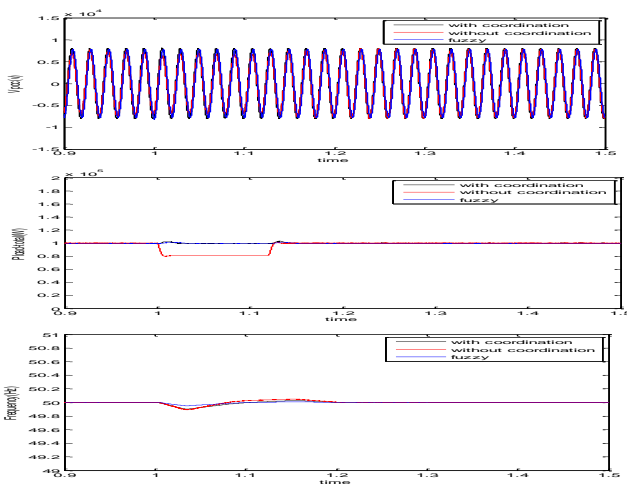

Fig 13. Operation behaviour of the microgrid under minor or temporary fault. (a) PCC voltage, (b) load power and (c) frequency response.

D. Minor fault simulation

In case of a temporary fault, the value of the fault resistance should be increased. Here also the three-phase external fault is situated nearer to the main-grid and the occurrence of the fault is considered at t=1sec and the fault resistance value is set at Rg=5Ω. The fault is removed after a duration of 120ms. The operation behaviour of the microgrid in temporary fault condition is as shown in Fig 13. The coordination of an active SFCL, SMES & the DG

units with FLC is better in assisting the microgrid to realize the FRT operation when compared with and without coordination. There could be a critical fault resistance Rgc, in cases where fault resistance is lower than Rgc, coordinated mode for the severe fault will be executed and otherwise coordination mode for the minor fault is applied.

In the event of a permanent fault with a low fault resistance, the value of the resistance can be varied from 0-2Ω and if a high fault resistance is considered, the value of the resistance can be set to 200Ω [18]. The simplified structure of a critical fault resistance is that Rgc=2Ω in our simulation analysis.
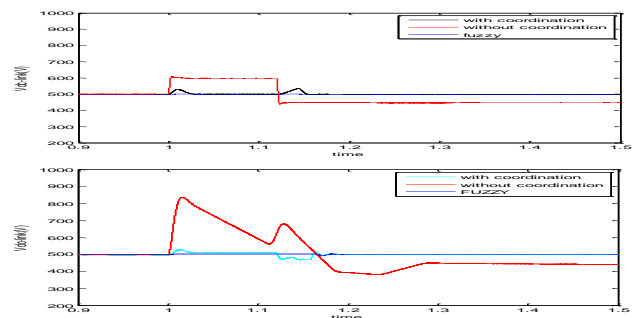

Fig 14. Effects of the coordination control on the PV1 generation DC-link over voltage under various faults. (A)Minor fault and (B) Severe fault.

Fig 14 demonstrates the effects of the coordination control on the PV generation (PV1 is selected) DC-link over voltage, due to permanent fault and temporary fault. The amplitude fluctuation and time frame of DC-Link over voltage are reduced with the help of fuzzy control coordination when compared with the conventional control coordination and without coordination. Therefore, the entire fluctuation process is well mitigated or smoothened, in order to secure the capacitor from the overvoltage source.

The outcome of the simulation analysis shows how it is helpful for the microgrid in maintaining the stability of PV generation and safeguarding it.

IV.   CONCLUSION

This paper proposes a well coordination of an active SFCL, SMES and the DG units with fuzzy logic controller to enhance the microgrid stability when short circuit fault occurs. The outcomes show the viability of the proposed coordination control with FLC, as it can accelerate the recovery of load, maintains the power balance, supresses the PCC fault current and mitigates the voltage-frequency fluctuation.

In the future scope, the advancement in the coordination control can be carried out in several ways, like a better control strategy can be employed for an Active SFCL, the SMES and the DG units. Improving the coordination control suitability for a big microgrid system with various DG resources. Moreover, the existing coordination does not take into account the impacts of load dynamics on microgrid transient performance, as only two static power loads are utilized.

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