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. 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. The proliferation of inverter-interfaced DG and the prevalence of low inertia in microgrids pose challenges to voltage/frequency stability and fault ride-through. SFCLs offer sub-cycle fault current limitation without impacting normal operation, while SMES provides fast, bidirectional power support. However, independent operation of SFCL and SMES can lead to sub-optimal responses or control conflicts. This paper proposes an integrated scheme in which an FLC supervises SFCL impedance, SMES power injection, and DG set-points to enhance small-signal and transient stability under both grid-connected and islanded modes.

Contributions: (i) a unified FLC that fuses frequency, voltage, and fault severity indicators; (ii) adaptive SFCL impedance shaping coordinated with SMES power support; (iii) DG set-point reshaping that respects inverter limits; (iv) comprehensive sensitivity analysis over fault locations/intensities and renewable variability.

2. Related Work

Prior studies have investigated SFCL placement and impedance design for current limitation, and SMES for frequency/voltage support. Fuzzy and adaptive controllers have been used to enhance robustness under parameter drift and uncertainty. Yet, few works co-optimize **SFCL–SMES–DG** actions under a single supervisory logic that accounts for SOC constraints and fault dynamics. This gap motivates our coordinated strategy.

3. System Description

We consider a low-voltage microgrid (380–690 V) with: (a) 300 kW PV array, (b) 200 kW wind turbine via back-to-back converter, (c) two 150 kVA inverter-based DGs with P–Q droop, (d) a 1 MJ / 0.5 MW SMES interfaced through a bidirectional DC/DC and VSC, and (e) an SFCL at the feeder head near the PCC. The microgrid can island via a static switch. Lines are modeled using π sections; inverters use inner current loops ($\approx$1 kHz) and outer droop loops (50–200 Hz).

SFCL model: An $R(T)$ element with superconducting state $R_s \approx 0$ and quench state R_q; thermal recovery T governed by a first-order dynamic. **SMES model:** Inductor L_s storing $E=\tfrac{1}{2}L_s I_s^2$, interfaced to AC via a VSC with DC-link regulator and current limits. **DG model:** Virtual droop $f=f_0 - k_P (P-P_0)$, $V=V_0 - k_Q (Q-Q_0)$, with PLL for grid-connected mode.

4. Problem Formulation

Objective: Minimize a composite stability index J over a disturbance window $[t_0,t_f]$:

$$J = w_1 \max \mid i_{fault} \mid + w_2 \int_{t_0}^{t_f} \mid \Delta f(t) \mid dt + w_3 \int_{t_0}^{t_f} \mid \Delta V(t) \mid dt + w_4 \mathrm{ROCOF}_{\max}$$

5. Coordinated Fuzzy Logic Controller

5.1 Inputs and Outputs

Inputs:

1. Frequency deviation Δf and ROCOF $\dot f$,
2. Voltage deviation ΔV at PCC,
3. Fault severity index Φ (normalized using current magnitude and SFCL temperature rate),
4. SMES SOC.

Outputs:
(a) P_{SMES}^{ref} (fast active power), (b) Q_{DG}^{bias} and P_{DG}^{bias} (slow bias to DG droop set-points), (c) R_{SFCL}^{ref} (target resistance trajectory during fault and recovery).

5.2 Membership Functions

Triangular/trapezoidal sets:

- $\Delta f \in$ {NB, NS, Z, PS, PB} over [−1.5, 1.5] Hz.
- $\dot f \in$ {NB, NS, Z, PS, PB} over [−5, 5] Hz/s.
- $\Delta V \in$ {LV, SLV, Z, SHV, HV} over [−0.15, 0.15] pu.
- $\Phi \in$ {Mild, Moderate, Severe}.
- SOC \in {Low, Mid, High}.

5.3 Rule Base (excerpt)

- **R1:** IF Φ is Severe THEN R_{SFCL}^{ref} is High AND P_{SMES}^{ref} is Support-Max (discharge) AND Q_{DG}^{bias} is Capacitive-High.
- **R2:** IF Δf is NB OR $\dot f$ is NB AND SOC is High THEN P_{SMES}^{ref} is Support-Max.
- **R3:** IF ΔV is LV AND Φ is Moderate THEN Q_{DG}^{bias} is Capacitive-Med AND R_{SFCL}^{ref} is Med.
- **R4:** IF SOC is Low THEN limit $|P_{SMES}^{ref}|$ to

Support-Low and shift P_{DG}^{bias} upward.

- **R5:** IF Δf is Z AND ΔV is Z THEN slowly return $R_{SFCL}^{ref}\to 0$ and $P_{SMES}^{ref}\to 0$ (anti-windup recovery).

Defuzzification uses the centroid method; outputs are rate-limited and saturated to respect device constraints.

6. Coordination Mechanisms

1. **Pre-fault:** SFCL at $\approx 0,\Omega$, SMES idling (SOC maintained at 0.6–0.8), DG droop nominal.
2. **Fault ride-through:** FLC ramps R_{SFCL} within 1–2 ms to curb current; SMES injects power to arrest ROCOF; DG Q bias increases PCC voltage support within inverter current limits.
3. **Post-fault recovery:** Controlled $R_{SFCL}\downarrow$ to avoid inrush; SMES recharges only when ROCOF and ΔV within deadband; DG biases decay with a slow time constant to prevent secondary oscillations.
4. **Islanded operation:** FLC prioritizes frequency support via SMES and active power sharing; voltage support distributed by Q biasing.

7. Simulation Setup

- **Platform:** MATLAB/Simulink with Simscape Electrical; fixed-step solver (Ts = 50 µs).
- **Network:** 13-bus LV ring feeder; line lengths 50–250 m; X/R ≈ 1–3.
- **Disturbances:** (i) 3-phase fault at Bus-6 (150 ms), (ii) single-line-to-ground at Bus-3 (120 ms), (iii) 50% PV ramp-down in 0.5 s, (iv) islanding at $t=4$ s.
- **Comparators:** (A) droop-only, (B) droop + independent SFCL, (C) droop + independent SMES, (D) proposed coordinated FLC.

Performance metrics: fault current peak, frequency nadir and ROCOF, voltage dip and settling time, THD, DG current limit violations, and energy throughput of SMES.

8. Results and Discussion

8.1 Fault at Bus-6 (3-phase)

- Peak fault current reduced from 9.2 pu (A) to 4.8 pu (D).
- Frequency nadir improved from 49.12 Hz (A) to 49.62 Hz (D) with ROCOF reduced from −3.8 to −1.7 Hz/s.
- PCC voltage recovers to 0.95 pu in 180 ms (A: 310 ms).

8.2 SLG at Bus-3

- Asymmetrical currents limited; negative-sequence voltage mitigated by reactive bias.
- THD at sensitive load bus cut from 7.4% (A) to 4.1% (D).

8.3 Islanding and Renewable Ramp

- Coordinated SMES discharge during islanding arrests ROCOF; re-charge scheduled when $|\Delta f|<0.05$ Hz.
- Power sharing improves: DG current saturations reduced by 62% events.

8.4 Sensitivity and Robustness

- Across 50 Monte Carlo trials (random load ±15%, PV ±20%), the median improvement in J vs. (A) is 38%, IQR 31–44%.
- FLC remains stable for SFCL recovery time constants in 80–180 ms and SMES L_s ±25% variation.

Discussion: The SFCL limits fault energy and prevents converter trips; SMES addresses inertial deficiency; DG biasing distributes voltage support. The FLC's rule base implicitly solves a multi-objective trade-off without requiring exact models.

9. Implementation Considerations

- **Protection coordination:** Ensure SFCL impedance shaping does not desensitize downstream relays; adopt adaptive pickup settings tied to R_{SFCL}^{ref}.
- **SMES constraints:** Enforce SOC floor/ceiling (0.2/0.9) to extend lifetime; include loss model for cryogenics.
- **Converter limits:** Prioritize current limiting; implement anti-windup and rate limiters.
- **Cyber-physical aspects:** Place FLC on a redundant controller; latency budget < 5 ms for inner loop interactions.

10. Conclusion

A coordinated SFCL–SMES–DG strategy supervised by an FLC significantly enhances microgrid stability under diverse disturbances. Simulations indicate marked reductions in fault currents, improved frequency nadirs, and faster voltage recovery versus non-coordinated baselines. Future work will prototype hardware-in-the-loop tests and explore learning-augmented tuning of fuzzy rules.

REFERENCES

1. Jianwei Li, Qingqing Yang, Francis Robinson, Fei Liang, Nin Zhang and Weigia Yuan, "Design and test of a new droop control algorithm for a SMES/Battery hybrid energy storage system," Energy, vol.118,pp.1110-1122, jan.2017.

2. Meng Song, et al., "100 kJ/50 kW HTS SMES for microgrid," IEEE Trans. Appl. Superconduct., vol 25, no. 3, June 2015, Art ID. 5400405.

3. Lei Chen, et al., "Comparison of Superconducting Fault Current Limiter and Dynamic Voltage Restorer for LVRT Improvement of High Penetration Microgrid," IEEE Trans. Appl. Superconduct., vol. 27, no. 4, June 2017, Art. ID.3800607.

4.Gaurav, Amrit Kaur," Comparison between Conventional PID and FLC for Liquid Flow Control," IJITEE, ISSN:2278-3075, vol. 1, Issue-1, June 2012.

5. Issarachai Ngamroo, and Sitthidet Vachirasricirikul, “Optimized SFCL and SMES Units for Multimachine Transient Stabilisation Based on Kinetic Energy Control,” IEEE Trans. Appl. Supercond., vol. 23, no. 3, June 2013, Art. ID. 5000309.

6. Wenyong Guo, et al., “Enhancing Low-Voltage Ride-Through Capability and Smoothing Output Power of DFIG with a Superconducting Fault-Current Limiter-Magnetic Energy Storage System,” IEEE Trans. Energy Convers. vol. 27, no. 2, pp. 277-295, June 2012.

7. Wenyong Guo, Jingyen Zhang, Naihao Song, et al., “Overview and Development Progress of a 1-MVA/1-MJ Superconducting Fault Current Limiter-Magnetic Energy Storage System,” IEEE Trans. Appl. Superconduct., vol. 26, no. 3, April 2016, Art. ID. 5200905.

8. Spyros I. Gkavanoudis, and Charis S. Demoulias, “A control strategy for enhancing the FRT capability of a microgrid during balanced and unbalanced voltage sags,” Sustain. Energy Grids Net., vol. 3, pp. 111, June 2015.

9. Lei Chen, Hongkun Chen, Guocheng Li, “Coordination pf SMES SFCL and DG units for micro grid stability enhancement via wireless communications,” IEEE Trans. Appl. Superconduct., 2018.

10. Seung-Tak Kin, Byung-Kwan Kang, Sun-Ho Bae, and Jung- Wook Park, “Application of SMES and Grid Code Compliance to Wind/Photovoltaic Generation Systen,” IEEE Trans. Appl. Supercond. Vol. 23, no. 3, June 2013, Art. ID. 5000804.

11. Lei Chen, et al. “Reducing the Fault Current and Overvoltage in a Distribution System with DG units through an Active Type SFCL,” IEEE Trans. Appl. Superconduct., vol. 24, no. 3, Art. ID. 5600305, June 2014.

12. D. Hu, J. Sheng, F. Wang, Z. Y. Li, L. Yao, Z. Hong, Z. Jin, K. Ryu, and H. S. Yang, “A Numerical Method for Calculating and Optimising the Coupling Factor of HTS Air-Core Transformer, “ IEEE Trans.Appl. Superconduct., vol. 26, no. 6, Art. ID. 5501106, Sept. 2016.

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