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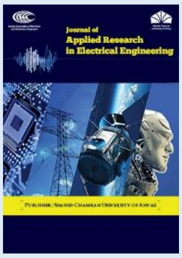

Research Article

Investigation of the Operation of Active Superconducting Fault Current Limiters in Distribution Networks Connected to Microgrids

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Abstract: Increasing the penetration level of distributed generation (DG) units in radial power distribution systems can increase the short-circuit level in these networks, which can, in turn, have destructive effects such as exceeding the tolerable current of the equipment and disrupting the protective coordination in the network. The active superconducting fault current limiter (ASFCL) is a new device that can limit fault current using voltage series compensation. This paper discusses the modeling of ASFCL and control strategies including fault detection and converter performance in normal and fault modes. Initially, its performance in limiting the fault current is investigated by simulating a sample three-phase system with ASFCL. In the next step, three operating modes including normal mode, upstream fault mode, and downstream fault mode are proposed to achieve an adaptive FCL that solves these problems in grid-connected microgrids. The simulation results confirm the proper performance of the ASFCL modes in both fault current limiting and protective coordination of overcurrent relays in the network.

Keywords: Fault current limiter, active superconducting current controller, grid-connected microgrid, protective coordination.

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1. INTRODUCTION

The recent growth of electrical energy demand and the rapid development of power systems have increased short-circuit phenomena, which can damage circuit breakers and other equipment. The deployment of current limiting equipment can be regarded as a useful solution for this issue [1]. Several studies have introduced and evaluated various types of FCLs. For example, the resistive, magnetic-shield, high-temperature superconducting, saturated iron-core, and shunt superconducting FCL types have been presented and examined [2-4]. These FCLs generally create a small impedance in the normal state and a large limiting impedance in the event of a fault.

When connecting a microgrid to the main grid, an FCL can be located between the upstream grid (main grid) and the downstream grid (micro-grid). The conventional type of FCLs generally performs a current limiting operation for both the upstream and downstream faults. Such operation of the conventional FCL can be useful when a short-circuit fault occurs in the main grid, but during a fault in the microgrid, the limiting impedance of the FCL may distort the coordination between the upstream and downstream OCRs [5].

The active superconducting fault current limiter (ASFCL) is a new generation of series compensations that combines superconducting transformers and series voltage converters [6]. This type of superconducting FCL can limit current limiting different levels.

In [12-14], some functional modes have been defined for the ASFCL only with the aim of fault current limiting in the main grid. The performance of the functional modes defined in these papers may disrupt the coordination of existing OCRs in the network. In [16], an ASFCL has been used to limit the fault current and to coordinate the existing OCRs in the main grid. However, the defined functional modes in [16] are not used for connecting the microgrid to the main grid. Also, in this reference, the relay coordination method is performed by changing the setting parameters of all of the OCRs in the network.

In [4], a unidirectional fault current limiter (UFCL) has been used to maintain the coordination between the upstream and the downstream OCRs. For this purpose, the FCL is deactivated for the downstream fault state. However, this may cause problems if the fault current exceeds the tolerable range of microgrid devices.

The main contribution of this paper is the protective coordination of all OCRs in the main grid and microgrid by defining appropriate operating modes in the event of upstream and downstream faults and without changing the relay setting parameters. In fact, by applying appropriate limiting impedances in different states of the network including upstream fault, downstream fault, and normal mode, the fault current is controlled and the coordination of all OCRs is maintained without changing the setting parameters of OCRs. The simulation results obtained using MATLAB confirm the effectiveness of the presented method.

2. DESCRIPTION AND MODELING

Fig. 1 shows the structure of a three-phase ASFCL employed in a typical three-phase circuit. The ASFCL consists of three superconducting transformers and a three-phase voltage source inverter. C_1 and C_2 are the split DC link capacitors. L_d and C_d are used to filter the harmonics generated by the PWM converter. The air-core superconducting transformer has some advantages compared to the conventional ones, such as the absence of iron losses and magnetic saturation, and lower transformer size and weight [12].

where A, B, and P are constants that are determined depending on the characteristics of OCRs. In this paper, the OCRs are assumed to have a very inverse characteristic. So, the corresponding constant values are 3.922, 0.0982, and 2, respectively [1]. $TDS_{primary}$ and $TDS_{back\text{-}up}$ are time dial settings of the primary and backup relays, respectively. The value of these parameters is calculated such that the primary and backup OCRs are coordinated. Also, M represents the plug setting multiplier (PSM) of the relay, which depends on the fault current and the current setting $I_{pick\text{-}up}$ of OCR.
The coordination time interval is defined as:

$$\Delta t = t_{back-up} - t_{primary} \tag{1}$$

The acceptable range of this parameter is normally a value between 0.2 and 0.5 seconds. Fig. 2 shows the flowchart of the coordination of OCRs by calculating the ASCC converter settings for the fault modes.

3. DESCRIPTION OF THE PROPOSED METHOD

To describe the proposed method, a typical distribution system connected to a microgrid is shown in Fig. 3. To provide the same performance in terms of fault current limiting for all the DG units, the ASFCL is placed between the upstream and downstream grid. With the occurrence of a short circuit in the downstream network, the FCL operation can lead to the loss of protective coordination of the downstream OCRs and the OCRs between the upstream and downstream networks.

To solve these problems, three operating modes are proposed for ASFCL regarding the location of the fault in the overall system. The fault direction at the ASFCL location (upstream or downstream) is detected using a directional relay. The operating modes are defined as follows:

Mode 1: Normal Operation Mode

As mentioned in Section 2, to neutralize the effect of the ASFCL in the main network, the output current and voltage of the converter must be set as:

$$i_{2a} = \frac{L_{S1}}{M_S} i_{1a} \tag{2}$$

$$u_{2a} = j\omega \frac{L_{S1}L_{S2} - M_S^{\,2}}{M_S} i_{1a} \tag{3}$$

where (u_{1a}, i_{1a}) and (u_{2a}, i_{2a}) are the primary and secondary voltage and current of the superconducting transformer, respectively.

Mode 2: Upstream Fault Mode

With the occurrence of a short circuit in the upstream network, the fault current without ASFCL and with ASFCL can be calculated as:

$$I_F = \frac{U_S - U_G}{Z_{T1} + Z_{T2}} \tag{4}$$

$$I_{F-withASCC} = \frac{U_S - U_G + j\omega M_S i_{2a}}{Z_{T1} + Z_{T2} + j\omega L_{S1}} \tag{5}$$

where U_S, Z_{T1}, U_G and Z_{T2} represent the equivalent source voltage and impedance of the upstream and downstream networks at the ASFCL location, respectively. According to (5), by adjusting the amplitude and angle of the converter output current (i_{2a}), the fault current can be adjusted to a suitable value so that the effect of increasing the current due to the application of new DG units is compensated.

Mode 3: Downstream Fault Mode

In this case, to reduce the voltage sag and thereby improve the power quality of the microgrid loads, ASFCL must operate in such a way that the minimum limiting impedance is applied to the network. It should be noted that the protective equipment of the microgrids is usually designed with high cut-off powers considering the future development of the microgrids. Therefore, in this case, the primary side voltage of the superconducting transformer of ASFCL can be set as:

$$u_{1a} = j\omega L_{S1} I_F - j\omega M_S i_{2a} = 0 \tag{6}$$

where I_F is equivalent to the fault current when the short circuit fault occurs in the downstream grid. The output current and voltage of the converter are calculated by (7) and (8):

$$i_{2a} = \frac{L_{s1}}{M_S} I_{FD} \tag{7}$$

$$u_{2a} = j\omega \frac{L_{S1}L_{S2} - M_s^{\,2}}{M_S} I_{FD} \tag{8}$$

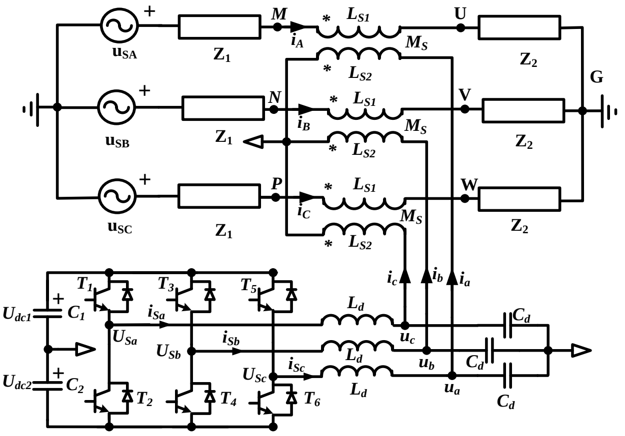

Fig. 1: The structure of a three-phase ASFCL.

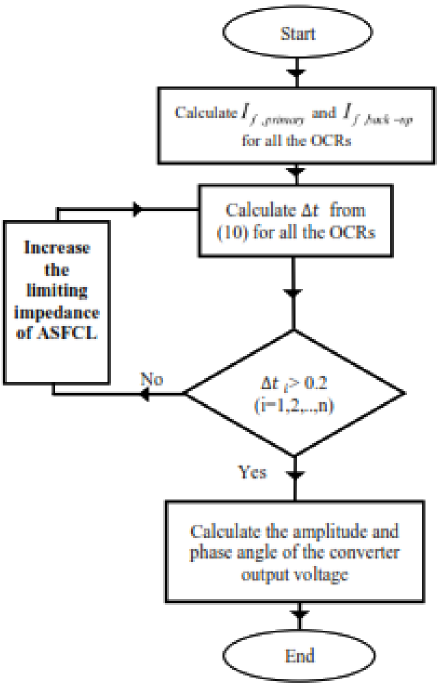

Fig. 2: The flowchart of the OCRs coordination by setting the ASFCL converter in faults mode.

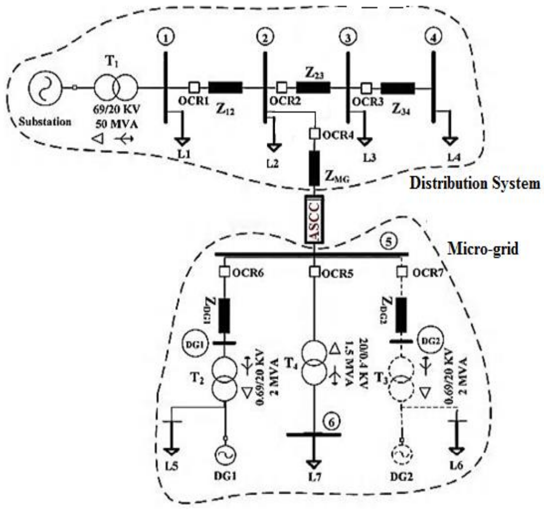

Fig. 3: A typical distribution system connected to a microgrid.

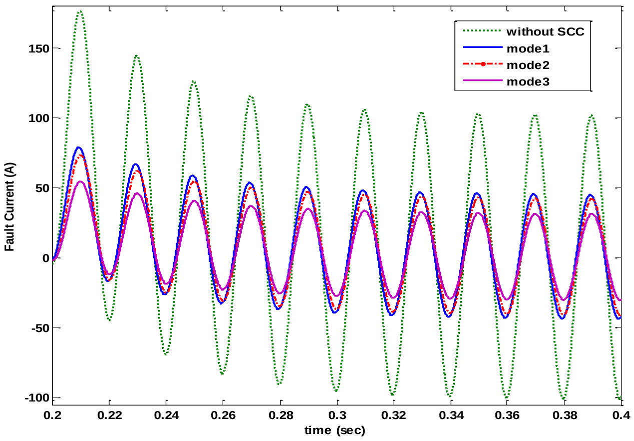

Fig. 4: The fault current without and with ASFCL.

4. SIMULATION RESULTS

This section simulates the ASFCL in different systems to test the fault current limitation and the coordination of the overcurrent relays.

4.1 Current Limiting Test

To test the operation of ASFCL on current limiting, the three-phase system shown in Fig. 1 with the parameters listed in Table 1 is simulated.

Fig. 4 shows the fault current without and with ASFCL. According to Fig. 4, the fault current is reduced to a suitable value in the presence of ASFCL. In addition, by adjusting the phase angle of the secondary current of the transformer to 90° (, i. e. mode 3), the highest effectiveness of the ASFCL in limiting the fault current is obtained.

The ASCC converter reference signals in the normal and fault modes are shown in Fig. 5. In the case of the single-phase fault, the AC components of U_{dc1} and U_{dc2} are opposite to each other, so the total DC voltage is kept at the level of 600 V.

Fig. 6 depicts the current and voltage waveforms of the superconducting transformer in the presence of the ASFCL. It is worthwhile to note that once a fault occurs, the fault current is suddenly reduced to a suitable level since, for the first cycle, the ASFCL with its original setting operates in mode 1. After fault detection, based on the control strategy of the converter, the ASFCL operates in mode 3, as it is the most effective in current limiting in this mode. In other words, the operating modes of ASFCL are selected based on the reference signals.

4.2 Investigating the Effect of ASFCL on the Protective Coordination of OCRs

In this section, the power system shown in Fig. 3 is simulated as a test system with the system data listed in Table 2 [1].

In this section, the IEC Standard 60909 [18] is used to calculate the short-circuit level, and the simulation results are analyzed in four different cases to investigate the coordination of over-current relays.

Case 1) Before Adding DG2

For the base case (before adding DG2), the values of setting parameters of OCRs are calculated as shown in Table

3. Fig. 7 illustrates the time-current curves (TCC) of all main and backup OCRs for Case1. The currents measured by the main and backup OCRs are calculated for the fault in front of the main relay. As shown in Fig. 7, by adjusting the relay parameters in accordance with Table 3, all the Δt_is are in an acceptable range. Therefore, the protective coordination of all OCRs has been carried out.

Case 2) DG$_2$ addition and without FCL

In this case, it is assumed that the relay settings are the same as those shown in Table 3. The operating times of the relays for this case are shown in Fig. 8. As shown in Fig. 8, in this case, the coordination time of the upstream OCRs (R1 and R2, as well as R2 and R3) are out of the acceptable range ($0.2<\Delta t<0.5$). Thus, the coordination between these relays is disrupted, but the coordination of the OCRs between the main grid and microgrid (R4 and R5, as well as R4 and R6) is preserved

Case 3) After DG2 addition with conventional FCL

In this case, a conventional FCL with the limiting impedance Z_{FCL}= 16 + 0.8j Ω is used in the tie feeder [1]. As shown in Fig. 9, the main grid OCRs coordination (R1 and R2, as well as R2 and R3) is preserved. However, due to the significant decrease in the fault current on the downstream side, the coordination of the OCRs between the main grid and microgrid (R4 and R5, as well as R4 and R6) is lost.

Case 4) After DG2 addition and with ASFCL

In this case, the effect of the ASFCL operating modes on the coordination of the OCRs is demonstrated. As shown in Fig. 10, with the occurrence of a short-circuit fault in the main grid, the ASFCL acts in mode 2 (the upstream fault mode) and the coordination between R1 and R2 and between R2 and R3 is preserved.

Furthermore, when a short-circuit fault occurs in the downstream network, the performance of the ASFCL in mode 3 preserves the coordination between the downstream OCRs by adjusting the fault current reduction, unlike the conventional FCL.

5. CONCLUSION

In this paper, an Active Superconducting Current Controller (ASFCL) was utilized as a voltage compensator type fault current limiter. It is placed between the main grid and microgrid to preserve the fault current level when a new DG unit is added to the microgrid. Various operating modes were defined for the ASFCL, including normal mode, upstream fault mode, and downstream fault mode. The performance of the ASFCL operation modes was compared to that of a conventional FCL for both upstream and downstream fault conditions. The simulation results show that with the occurrence of a short-circuit fault in the main grid, both ASFCL and conventional FCL have a positive effect on the coordination of the overcurrent relays and power quality of microgrid loads. On the other hand, when a short-circuit fault occurs in the microgrid and a conventional FCL is used, the coordination of the OCRs in the downstream network is violated and the power quality of the microgrid loads is reduced due to an increase in the voltage sag of these loads. The results also confirm that the application of the ASFCL with the proposed operating modes for this case resolves the mentioned problems. Thus, the ASFCL with the proposed method outperforms the conventional FCL.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ahmad Ghafari: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Software. **Mohsen Saniei**: Funding, Supervision, Validation, Roles/Writing - original draft, Writing - review & editing. **Morteza Razaz**: Supervision, Writing - review & editing. **Alireza Saffarian**: Supervision, Writing - review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

Table 1: The parameters of the simulated system

Parameter	Value
$[U_{SA}, U_{dc}]$	[220,600] (V)
Z_1	0.19 + 2.16 i (Ω)
Z_2	15 + 2 i (Ω)
F	50 (Hz)
$Ls_1=Ls_2$	10 (mH)
$[M_s, L_f]$	[9, 6] (mH)
$C_1=C_2$	2000 (μF)
C_f	30 (μF)

Table 2: Data of the test system

The network components	Data
Main substation	U_{nQ}=69KV, S''_{kQ}=1000MVA
Transformer (T_1)	S=50MVA, 69/20KV, u_k=20.5%
Z_{12}-Z34	2.75+4.15j
ZMG	2.15+3.24j
L1-L4	S=20MVA, PF=0.94
DG_1	S_{rG}=1.5MVA, U_{rG}=690V,
T_2 and T_3	S=2MVA, 0.69/20KV, u_k=6%
T_4	S=1.5MVA, 20/0.4KV, u_k=6.5%
Z_{DG1}	0.081+0.057j
Z_{DG2}	0.162+0.114j
L_5 and L_6	S=1.2MVA, PF=0.95
L_7	S=0.9MVA, PF=0.97

Table 3: Setting values for each OCR for the base case

Relay unit	Max. Load current (A)	CT ratio	Pick-up Current	TDS
OCR1	800	1000/5	5.496	0.4
OCR2	488	500/5	7.636	0.2
OCR3	220	300/5	5.5	1.1
OCR4	60	100/5	4.5	1
OCR5	15	100/5	1.5	1.9
OCR6	75	100/5	5.62	2.7

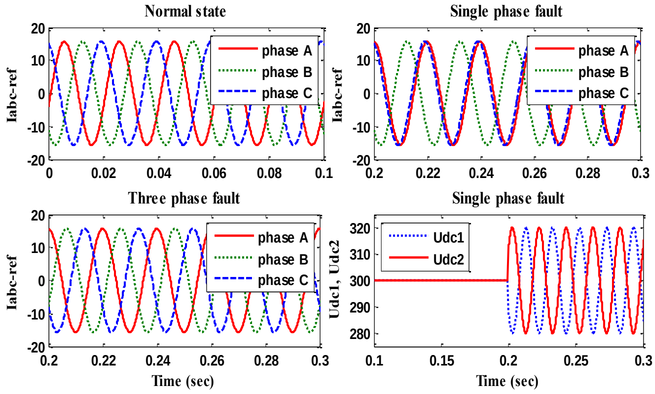

Fig. 5: The reference signals of the ASFCL converter in normal and fault states

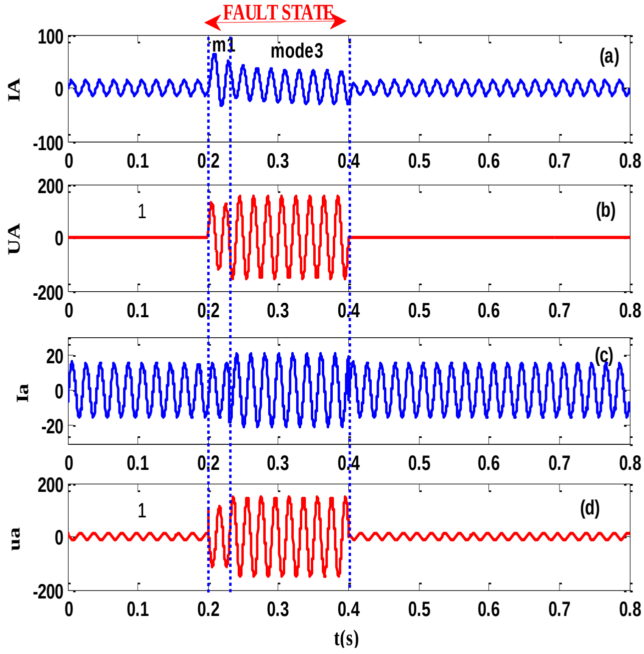

Fig. 6: The waveforms of the primary and secondary currents and voltages of the superconducting transformer

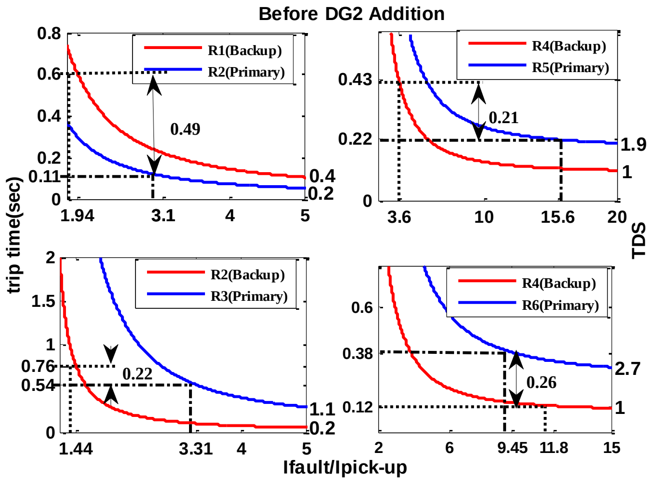

Fig. 7: The time-current curves of OCRs before adding DG2

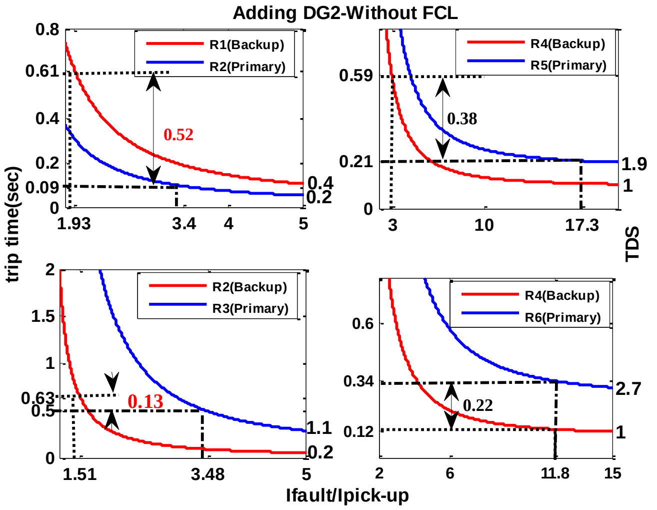

Fig. 8: The time-current curves of OCRs after DG2 addition and without FCL

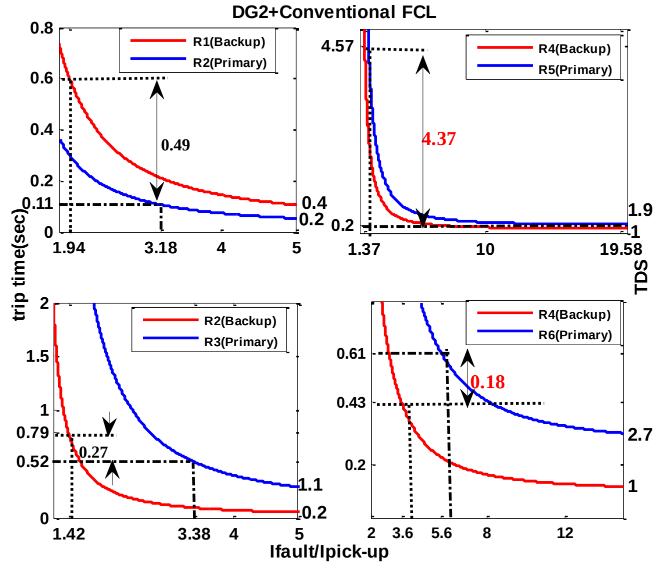

Fig. 9: The time-current curves of OCRs after adding DG2 and with conventional FCL

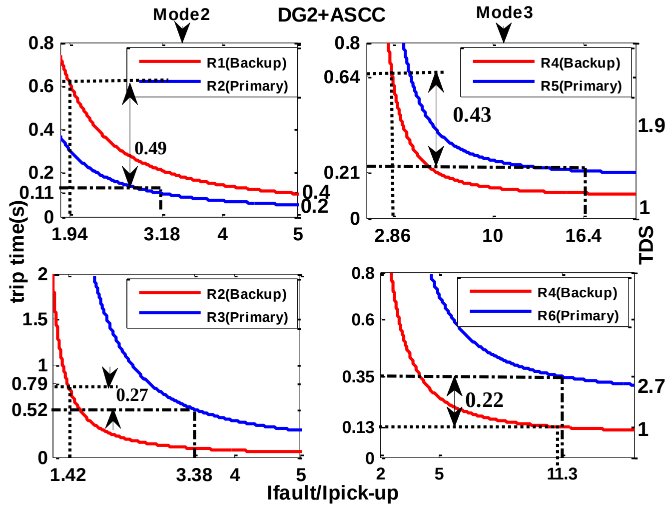

Fig. 10: The time-current curves of OCRs after adding DG2 and with ASFCL

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BIOGRAPHY

Ahmad Ghafari Gusheh was born in 1987 in Shahrekord, Iran. He received his B.Sc. degrees in electrical engineering from Islamic Azad University of Najafabad, Najafabad, Iran in 2009 and his M.Sc and Ph.D. degrees in electrical engineering from Shahid-Chamran University of hvaz, Iran in 2012 and 2021, respectively. His main research interests are power system protection, microgrid, and power distribution systems.

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