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A Multivariable Fuzzy Rule-based Relay for Short Circuits in AC Micro-grids

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Abstract

Objectives: This work seeks to present a new protective relay for short circuits in AC micro-grids, under different control strategies as well as in both grid-connected and islanded modes of operation. **Methods/Statistical Analysis:** An index test-bed which consists of two wind turbines as micro-sources and other requisite network elements is developed. From the dynamic short circuit analysis of the test-bed, the rules which govern interaction of four parameters are framed in fuzzy form. Using the framed rules, fuzzy logic controllers are designed for micro-source and feeder sub-relays. The hardware of each sub-relay is realized in SimPowerSystems using combinational logic components. **Findings:** Offline and online response tests of the proposed relay show that it generates logic 1 during short circuits and logic 0 during normal operating conditions in both grid-connected and islanded modes of operation of the micro-grid. The proposed relay also provides equivalent response under both voltage and reactive power control strategies. This is consistent with response of a reliable protective relay as reported in related literature. The proposed relay also supports plug-and-play and peer-to-peer requirements of micro-grids. Similar to digital relays reported in literature, the proposed relay is a departure from classical relays wherein protection is based on threshold of short circuit current. In the proposed relay, protection is based on parameters of micro-sources and feeders. **Application/Improvements:** The proposed relay finds use in providing protection for personnel and system against short circuit currents. It reliably protects against single line-to-ground, line-to-line and three-phase bolted short circuits.

Keywords: Fuzzy, Micro-grids, Multivariable, Relay, Short Circuits

1. Introduction

The primary aim of a micro-grid is to provide quality, reliable and sustainable power to a load center[1]. The micro-grid is a form of Distributed Generation (DG) and a building block of smart grid which essentially operates using advanced control architecture and quality protection. A micro-grid may have energy storage system and it may run autonomously or in grid-connected mode[2–4].

The benefits, topology and control of micro-grids are well established[5–7]. However, a proper design of protection scheme remains challenging owing to the nature of DG micro-sources within the distribution system[8,9]. Power flow in a micro-grid could be two-way[10], such as energy storage or plug-in electric vehicles[11–13]. The change of DG micro-source from passive to active mode results in loss of native radial form of the distribution system. This requires new evaluation for relay settings and coordination, coming with a number of challenges on over-current protective devices, including blinding of protection, false tripping, loss of fuse-re-closer coordination, non-synchronized reclosing and disabling of automatic reclosing[14–17]. A summary of the protective systems in literature is provided in Figure 1. The Figure provides an overview of micro-grid's protective systems in literature using their working principles which are based on measurement and requisite combination of primary quantities (such as current) and derived quantities (such as impedance).

In 1997, in[18] proposed a new method for determining and improving the Time Dial Setting (TDS) and operating time of

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an Over-Current (OC) relay. The proposed method is based on neural network and fuzzy logic. The improved TDS is obtained using a full "counter-propagation" neural network while the improved operating time is obtained through use of fuzzy logic. The inputs to the fuzzy logic processor are TDS, Plug Setting Multiplier (PSM) and the existing over-current relay characteristic. The proposed method simply improves the operating time of the test relay. The scheme does not propose a relay suitable for micro-grid application.

In[19] proposed an over-current protection for fault identification in a radial power system based on fuzzy logic. The inputs to the proposed fuzzy processor are the RMS values of current. The fuzzy processor is based on "If-Then" rules. Its de-fuzzification is based on the Centre of Area method proposed. The proposed relay is simple, low-cost and fulfils the peer-to-peer requirement of micro-grid. It also offers protection for both balanced and unbalanced faults in a radial feeder. However, its applicability is limited to only fault detection in a feeder without ability to make a relaying judgment to clear the fault by isolating faulted circuit. It also does not satisfy the plug-and-play requirement of micro-grid.

In[20] proposed a Digital Signal Processor-based over-current relay based on fuzzy logic. The Digital Signal Processor (DSP) performs computation and generation of data in real time. The relay operates on measurement of current and voltage, though called over-current relay. The relay is simple and cost-effective, since its realization is based on inexpensive solid-state devices. It also fulfils the peer-to-peer requirement of micro-grid. However, a key deficiency of the relay is the fact that it is a component-based protective system. Operation of the micro-grid entails system-wide protection in order to ensure reliable, cost-effective, speedy, selective and sensitive operation in addition to component-based protection provided by existing systems. Also, it cannot be used to provide protection for micro-sources which are requisite sub-systems of micro-grids. The proposed relay is fundamentally a modification of existing over-current protection and it does not satisfy the plug-and-play requirement of micro-grids, since addition of micro-sources requires system reconfiguration.

A summary of the drawbacks associated with protective systems in literature includes the fact that some provide only component-based protection, while others fail to simultaneously satisfy the plug-and-play and peer-to-peer requirements of micro-grids. While others are potentially harmful to system and personnel, some require use of communication infrastructure which makes them capital intensive and vulnerable to communication failures. Finally, all the proposals found in literature have been investigated without simulating or considering the effect of operational control strategy. In practice, control dictates system's parameters and consequently, system's response to short circuits. This paper proposes a new protective system for ac micro-grids. The proposed Multivariable Fuzzy Rule-based relay (MFR) has been investigated under two control strategies.

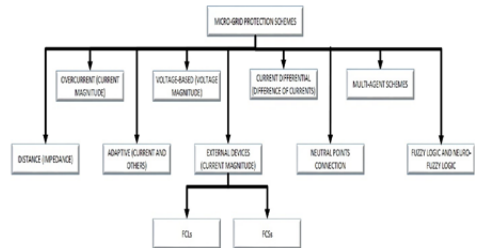


Figure 1. An overview of proposed protective schemes for micro-grids based on operational principles.

1.1 Research Motivation

The difference between normal operating parameters and abnormal operating parameters is not crisp in a micro-grid with grid-connection capability as published in[21]. Normally, a short circuit current magnitude in a grid-connected micro-grid could be so small that it is a normal condition in the utility and the utility protection becomes blinded[22]. On the other hand, a utility short circuit could be a normal operating condition in a grid-connected micro-grid due to the controlling effect of the converters in the micro-grid. This lack of clear separation of normal and abnormal operating boundaries in a micro-grid capable of utility connection is properly defined using fuzzy logic theory. Thus, variation of the critical parameters to short circuits under different conditions (islanded or grid-connected, V or Q control) is not crisp but fuzzy. This fuzziness in the boundaries of these parameters presents challenges to use of existing protection such as over-current devices as published in[23]. This paper therefore presents a new protective relay for short circuits in ac micro-grids using fuzzy logic. The proposed relay consists of two sub-relays: micro-source sub-relay and feeder sub-relay.

1.2 Design of Control Systems for the Index Test Bed

The index test bed is subjected to time-domain step response analysis. The system is found to be stable but exhibits poor response. Regulators are then designed and realized in closed-loop feedback architecture. The systems designed are pitch angle regulator, active power regulator, reactive power regulator, grid AC voltage regulator, DC bus voltage regulator, grid-side converter current regulator and rotor-side converter current regulator. The design resulted in stable system with satisfactory response. Thereafter, the regulators are combined to implement two mutually exclusive control regimes: The active power-voltage (PV or V) control and the active-reactive power (PQ or Q) control. When the micro-grid is operated in V control, the voltage controller keeps the grid voltage constant with a 4% droop. When it is operated in Q control, the var controller keeps the reactive power at the grid constant by injecting or absorbing reactive power[24].

2. Micro-Source and Feeder Parameters

The rated micro-source voltage, current, active power and reactive power are given in (1) to (4). The sub-relays detect onset of short circuits by comparing actual micro-source and feeder flows with their rated capacities plus allowable tolerance in terms of voltage, current, active power and reactive power.

2.1 Micro-Source

The micro-source in the test bed used in this study is a wind turbine generator based on doubly-fed induction generator. The rated rotor and stator voltages of the micro-source are provided in (1).

$$\left.\begin{aligned} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} &= R_s \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_{as} \\ \phi_{bs} \\ \phi_{cs} \end{bmatrix} \\ \begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix} &= R_r \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_{ar} \\ \phi_{br} \\ \phi_{cr} \end{bmatrix} \\ v_{\alpha\beta\gamma} &= \frac{2}{3}\begin{vmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix} \begin{vmatrix} v_a \\ v_b \\ v_c \end{vmatrix} \\ v_m &= v_\alpha \end{aligned}\right\} \quad 1$$

Where,

v, i and ϕ represent phase voltage, current and flux linkages, respectively.

Subscripts a, b and c represent phases a, b and c, respectively.

Subscripts r, s and m represent rotor, stator and micro-source quantities, respectively.

The rated current expected to flow from the micro-source to the grid is given in (2).

$$\left.\begin{aligned} i_s &= \frac{E' - v_s}{jX'} \\ i_r &= \frac{1}{X_m X'}\left[jv_s\left(X' - X_s\right) + jX_s E' \right] \\ I_m &= i_s + i_r \end{aligned}\right\} \quad 2$$

Where,

E', X', X_m and I_m are fictitious voltage, reactance associated to the fictitious voltage source, rotor-stator mutual reactance and micro-source current, respectively.

The rated active power flowing between the micro-source and the grid is given in (3).

$$\left.\begin{aligned} P_m &= P_s + P_r \\ P_m &= -\frac{v_s E_{eq}}{X_{eq}} \sin\left(\theta - \delta\right) \end{aligned}\right\} \quad 3$$

Where,

P_m, P_s and P_r are active powers of micro-source, stator and rotor, respectively.

E_{eq}, X_{eq}, θ and δ are controllable voltage magnitude, reactance associated to the controllable voltage, rotor angle and controllable voltage angle, respectively.

The rated reactive power exchange between the micro-source's reactive var source and the grid is given in (4).

$$\left.\begin{aligned} Q_m &= Q_s \\ Q_m &= \frac{v_s E_{eq}}{X_{eq}} \cos\left(\theta - \delta\right) - \frac{v_s^2}{X_{eq}} \end{aligned}\right\} \quad 4$$

Where,

Q_m and Q_s are respectively reactive powers in micro-source and stator[25].

A description of the parameters used for micro-source sub-relay is provided as follows:

- P_m = Nominal three phase active power from micro-source, obtained by summing the three phase components via a summing circuit.
- Q_m = A defined three phase reactive var of micro-sources obtained during normal operation.
- V_α = Alpha axis voltage obtained using Clarke's transformation.
- I_m = Absolute value of the vector sum of the complex stator current in abc reference frame.

2.2 Feeder

The rated feeder current, voltage, active power and reactive power are given in (6) to (8).

The feeder voltages and currents in abc reference frame are transformed to their symmetrical components using (5).

$$\left.\begin{aligned} A^{-1} &= \tfrac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \\ \alpha &= 1\angle 120^o \end{aligned}\right\} \quad 5$$

The feeder current I_f is given in (6).

$$\left.\begin{aligned} I_f &= \frac{1}{\sqrt{3}v_f}\left(P_f + jQ_f\right) \\ \begin{vmatrix} I^o \\ I^+ \\ I^- \end{vmatrix} &= A^{-1}\begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} \\ I_2 &= I^- \end{aligned}\right\} \quad 6$$

Where,

I^o, I^+ and I^- are zero-, positive- and negative-sequence currents, respectively.

The voltages associated to the feeder are described in (7).

$$\left.\begin{aligned} \begin{vmatrix} V^o \\ V^+ \\ V^- \end{vmatrix} &= A^{-1}\begin{vmatrix} v_a \\ v_b \\ v_c \end{vmatrix} \\ V_1 &= V^+ \end{aligned}\right\} \quad 7$$

Where,

V^o, V^+ and V^- are zero-, positive- and negative-sequence voltages, respectively.

The active and reactive powers in a feeder are described in (8).

$$P_f + jQ_f = \tfrac{1}{2}\left(v_a i_a^* + v_b i_b^* + v_c i_c^*\right) \quad 8$$

Where,

i_a^*, i_b^* and i_c^* are the complex conjugates of i_a, i_b and i_c, respectively[26].

A description of the parameters used for feeder sub-relay is provided as follows:

- P_f = Three phase active power rating of the feeder.
- Q_f = Three phase reactive power rating of the feeder.
- V_1 = Positive sequence feeder voltage.
- I_2 = Negative sequence feeder current.

Using (1) to (8), the attributes of both micro-source and feeder under simulated short circuits are developed and presented in subsequent sections.

3. System Under Study

From the results of simulation performed on the index test bed and by using (1) to (8) for measurement, characteristics of the four parameters are summarized and presented in both grid-connected and islanded modes of micro-grid operation under V and Q controls during short circuits. In both grid-connected and islanded modes, three phase-to-earth bolted short circuit fault is applied at 30.00 s and withdrawn at 32.00 s. The duration of 2-second is sufficient to allow the micro-grid respond to external stress. The stress is also introduced at a time that the micro-sources have achieved steady-state. Dynamic simulation of the test bed (synch. generator, micro-grid feeders and DFIG) under short circuit is performed for 50.00 simulation seconds. The responses of the test bed for different short circuit locations and DFIG controller in V and Q controls are obtained and summarized in Tables 1 to 3.

Table 1. Summary of micro-source parameters during utility and micro-grid short circuits in grid-connected mode

Utility SC		**Micro-grid SC**	
Parameter	Behavior (summary)	Parameter	Behavior (summary)
P	→	P	↓ ~~
Q	$\uparrow_{V}$, $\rightarrow_{Q}$	Q	↑ ~~
V	↓ ~~	V	↓ ~~
I	↑ ~~	I	↑ ~~

Table 2. Summary of feeder parameters during utility and micro-grid short circuits in grid-connected mode

Utility SC		**Micro-grid SC**	
Parameter	Behavior (summary)	Parameter	Behavior (summary)
P	↓ ~~	P	↓ ~~
Q	↑ ~~	Q	↓ ~~
V	↓	V	↓ ~~
I	↑	I	↑ ~~

Table 3. Summary of micro-source and feeder parameters during micro-grid short circuits in islanded mode

Micro-source		**Feeder**	
Parameter	Behavior (summary)	Parameter	Behavior (summary)
P	↓ ~~	P	↓
Q	↑ ~~	Q	↓
V	↓	V	↓
I	↑	I	↑

3.1 Grid-connected Mode

Under grid-connected mode, the attributes of the four parameters associated with a micro-source during utility and micro-source short circuits are summarized and presented in Table 1.

In the grid-connected mode, the active power generated by the micro-source steadies during utility short circuit while it drops during micro-grid short circuit. This is because the contribution of the micro-grid to utility short circuits is minimal relative to micro-grid as a result of large impedance between the utility and micro-source, good fault-ride-through capability of utility, power electronic-interfacing of micro-source and its smaller short circuit capacity. In both cases, severe post-fault oscillation is observed in the micro-source due to relatively smaller inertia, as shown in Table 1.

Under grid-connected mode, the attributes of the four parameters associated with a feeder during utility and micro-source short circuits are summarized and presented in Table 2.

3.2 Islanded Mode

In islanded mode, the attributes of the four parameters associated with a micro-source and a feeder under micro-grid short circuits are summarized and presented in Table 3.

4. Development of Fuzzy Controller for Short Circuit Protection

The fuzzy logic controller inputs are normalized using per unit of the four parameters: Active power (P), reactive power (Q), voltage (V) and magnitude of current (I). The input parameters are defined in (9) to (16).

$$P_{mn} = \frac{P_{ma}}{P_m} \tag{9}$$

Where,

P_{ma} = Actual micro-source active power.

$$Q_{mn} = \frac{Q_{ma}}{Q_m} \tag{10}$$

Where,

Q_{ma} = Actual micro-source reactive power.

$$V_{\alpha n} = \frac{V_{\propto a}}{V_{\propto}} \tag{11}$$

Where,

$V_{\alpha a}$ = Actual α-axis micro-source voltage magnitude.

$$I_{mn} = \frac{I_{ma}}{I_m} \tag{12}$$

Where,

I_{ma} = Actual micro-source current magnitude.

A description of the input parameters for micro-source sub-relay is provided as follows:

- P_{mn} = Nominal zed micro-source active power ratio.
- Q_{mn} = Normalized micro-source reactive power ratio.
- $V_{\alpha n}$ = Normalized α-axis micro-source voltage ratio.
- I_{mn} = Normalized micro-source current ratio.

$$P_{fn} = \frac{P_{fa}}{P_f} \tag{13}$$

Where,

P_{fa} = Actual feeder active power.

$$Q_{fn} = \frac{Q_{fa}}{Q_f} \tag{14}$$

Where,

Q_{fa} = Actual feeder reactive power.

$$V_{1n} = \frac{V_{1a}}{V_1} \tag{15}$$

Where,

V_{1a} = Actual feeder positive sequence voltage magnitude.

$$I_{2n} = \frac{I_{2a}}{I_2} \tag{16}$$

Where,

I_{2a} = Actual feeder negative sequence current magnitude.

A description of the input parameters for feeder sub-relay is provided as follows:

- P_{fn} = Normalized feeder active power ratio.
- Q_{fn} = Normalized feeder reactive power ratio.
- V_{1n} = Normalized feeder positive sequence voltage magnitude ratio.
- I_{2n} = Normalized feeder negative sequence current magnitude ratio.

The output of the fuzzy logic controller is either logic 0 (Close CB) or logic 1 (Open CB). The proposed relay controller consists of two sub-controllers; micro-source sub-controller and feeder sub-controller. Either of the sub-controllers generates a logic response which depends on its input conditions and the rules embedded in it. The rules are developed in Section 4.2.

4.1 Membership Functions

Membership functions are used to fuzzify each of the input parameters of the micro-source as shown in Figure 2. In Simulink Fuzzy Logic Toolbox, Gaussian membership functions are used with three linguistic characteristics for P_{mn}, Q_{mn}, $V_{\alpha n}$, P_{fn}, Q_{fn} and V_{1n} each, while either of I_{mn} and I_{2n} has two linguistic characteristics. In this work, the Gaussian function provided in (17) is used.

$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}} \quad (17)$$

Where,

a is the height of the curve's peak.

b is the position of the center of the curve's peak.

c is the Gaussian rms width which controls the width of the curve.

The degree of membership for each input parameter is developed as follows:

4.1.1 Micro-source

- The micro-source active power ratio (P_{mn}) is described using three linguistic characteristics as shown in Figure 2(a). Active power flow in the micro-source is unidirectional. Using Gaussian function defined in (17) and to enable it generate active power from 0 p.u. to 1.2 p.u. of its rated power, then,

LOW $\rightarrow$ The Gaussian plot is centered at 0.
NORMAL $\rightarrow$ The Gaussian plot is centered at 0.6.
HIGH $\rightarrow$ The Gaussian plot is centered at 1.2.

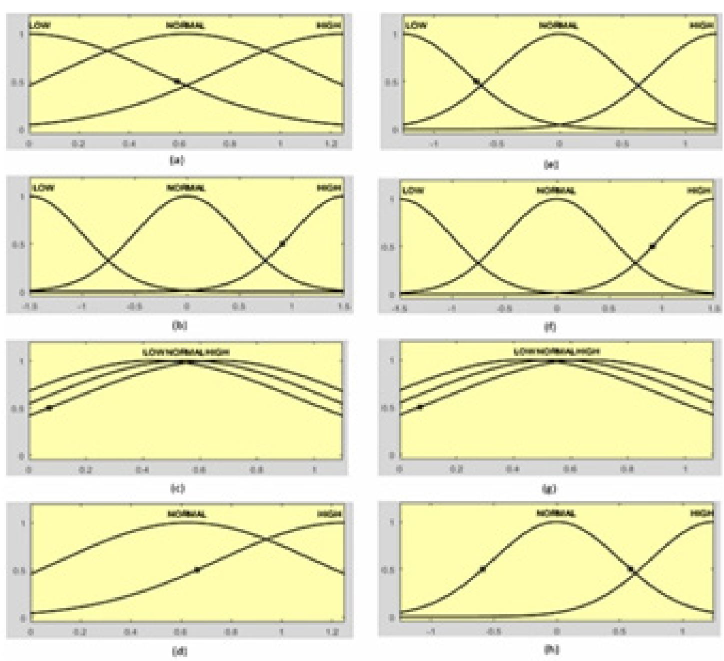
Similar concept is applied to formulate the degree of memberships for Q_{mn}, $V_{\alpha n}$ and I_{mn}.

4.1.2 Feeder

- The feeder active power ratio (P_{fn}) is described using three linguistic characteristics as shown in Figure 2(e). Active power flow in the feeder is bidirectional. Using Gaussian function and to allow 25% overload, then,

LOW $\rightarrow$ The Gaussian plot is centered at -1.25.
NORMAL $\rightarrow$ The Gaussian plot is centered at 0.
HIGH $\rightarrow$ The Gaussian plot is centered at +1.25.

Similar concept is applied to formulate the degree of memberships for Q_{fn}, $V_{\alpha n}$ and I_{mn}.



(a) Micro-source active power ratio, P_{mn}. (e) Feeder active power ratio, P_{fn}.
(b) Micro-source reactive power ratio, Q_{mn}. (f) Feeder reactive power ratio, Q_{fn}.
(c) Micro-source voltage ratio, $V_{\alpha n}$. (g) Feeder voltage ratio, V_{1n}.
(d) Micro-source current ratio, I_{mn}. (h) Feeder current ratio, I_{2n}.

Figure 2. Membership function plots for micro-source sub-relay and feeder sub-relay input parameters.

4.2 Developing Fuzzy Rules

Fuzzy logic rules are developed using a combination of experience, IEC standard[27], trial and error until the rules are optimized. This is done in Simulink Fuzzy Logic Toolbox, resulting in three rules for either of micro-source and feeder sub-relays. A total of six rules in the form of "IF-and-Then" are developed for the proposed fuzzy logic controller. Other possible combinations of the input parameters are invalid in the context of the system under study (typically, current magnitude will not fall under any short circuit, control regime or operating mode). The purpose of using Simulink Fuzzy Logic Toolbox in this work is to frame optimized rule set which best describes the four parameters. The response of the fuzzy controller is then simulated and the optimal rule set is extracted. The hardware of extracted rule set is realized using combinational logic devices in SimPower systems. The framed optimal rules are given as follows:

Micro-source sub-relay

- ***IF P_{mn} is NORMAL AND Q_{mn} is NORMAL AND $V_{\alpha n}$ is NORMAL AND I_{mn} is NORMAL; Then, Close Output (Logic 0).***
  - ***IF $V_{\alpha n}$ is LOW AND I_{mn} is HIGH; Then, Open Output (Logic 1).***
  - ***IF $V_{\alpha n}$ is NORMAL AND I_{mn} is HIGH; Then, Open Output (Logic 1).***

Feeder sub-relay

- ***IF P_{fn} is NORMAL AND Q_{fn} is NORMAL AND V_{1n} is NORMAL AND I_{2n} is NORMAL; Then, Close Output (Logic 0).***
  - ***IF P_{fn} is LOW AND Q_{fn} is LOW; Then, Open Output (Logic 1).***
  - ***IF P_{fn} is LOW AND Q_{fn} is HIGH; Then, Open Output (Logic 1).***

Table 4 provides a summary of the membership functions of the input parameters.

4.3 De-fuzzification

The rules are executed in the Simulink Fuzzy Inference System (FIS) and de-fuzzification is performed based on the data acquired during rules evaluation. De-fuzzification is performed using cetroid method in the FIS system. The crisp values are obtained from the de-fuzzification process and the controller takes a decision based on the result of de-fuzzification. Typically, for the micro-source when $P_{mn} = 0.8$, $Q_{mn} = 0.7$, $V_{\alpha m} = 0$ and $I_{mn} = 1$, the output from the de-fuzzification process is 0.923. This is a "HIGH" and is digitally processed to 1. This scenario is shown in Figure 3.

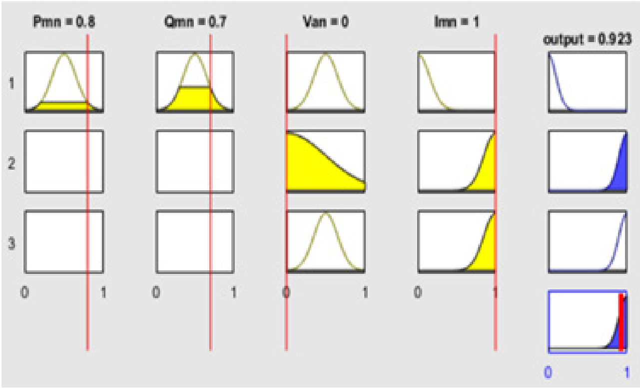


Figure 3. De-fuzzification process.

4.4 Fuzzy Logic Controller's Response

Using the developed fuzzy logic rules, fuzzy logic controllers are designed for both sub-relays. For the micro-source sub-relay, the controller inputs are P_{mn}, Q_{mn}, $V_{\alpha n}$ and I_{mn} while its output is logic 0 (close CB) or logic 1 (open CB). The controller is modeled such that when all inputs are normal, the output remains closed. However, when the input parameters violate the normal operating rule (this is a short circuit fault), the controller sends a trip signal (logic 1) to the CB. When normal operating rules are fulfilled, the controller recloses the CB.

Table 4. Membership functions associated with micro-source and feeder sub-relays

Micro-source				Feeder			
Parameter	Centre of Gaussian curve			Parameter	Centre of Gaussian curve		
	LOW	NORMAL	HIGH		LOW	NORMAL	HIGH
P_{mn}	0	0.6	1.2	P_{fn}	−1.25	0	1.25
Q_{mn}	−1.5	0	1.5	Q_{fn}	−1.5	0	1.5
$V_{\alpha n}$	0.44	0.55	0.66	V_{1n}	0.44	0.55	0.66
I_{mn}	-	0.625	1.25	I_{2n}	-	0	1.25
Output		CLOSE	OPEN	Output		CLOSE	OPEN
		0	1			0	1

For the feeder sub-relay, the controller inputs are P_{fn}, Q_{fn}, I_{2n} and V_{1n}. When all inputs are normal, the output remains closed. However, when any input is not normal, the controller sends a trip signal (logic 1) to the CB.

5. Proposed MFR Relay, Connection Schemes and Response Tests

The relay hardware is implemented using software. Its realization is achieved in software implementation of the requisite rules using combinational logic devices. The micro-source sub-relay consists of logic gates (AND, OR, NOT and XOR). The gates are combined such that they realize the optimized logical rules which combine the four inputs (P_{mn}, Q_{mn}, V_{an} and I_{mn}) such that the micro-source sub-relay instantly outputs a logic 1 once a short circuit occurs either in the utility or in the micro-grid and regardless of the control strategy. The optimized logical rules are extracted from the verbal rules embedded in the MATLAB's Fuzzy Inference System. The four inputs are ratios measured from the micro-source. The feeder sub-relay is implemented using concepts and methodology similar to the micro-source sub-relay but with four inputs (P_{fn}, Q_{fn}, V_{1n} and I_{2n}) being ratios measured from the feeder. The outputs of the two sub-relays are combined using an OR gate, forming a composite relay for both micro-source and feeder, as shown in Figure 4.

Either sub-relay is implemented using distinct fuzzy rule combination of the four measured parameters such that regardless of the control regime and operating mode, a micro-source short circuit fault is instantly detected by the micro-source sub-relay while a feeder short circuit fault is instantly detected by the feeder sub-relay. Also, depending on its severity, a utility fault is detected by either feeder sub-relay or both sub-relays.

The proposed MFR relay could be connected in two schemes: the unit scheme and the sub-unit scheme. In the unit scheme, the outputs of the two sub-relays are combined via an OR gate to output a single logic. This output then controls a dedicated CB such as at the PCC. In the sub-unit scheme, the output of the micro-source sub-relay controls a CB associated with output terminals of a micro-source. Similarly, the output of the feeder sub-relay controls a CB associated with a feeder. In both schemes, the micro-source sub-relay receives inputs from its associated micro-source while the feeder sub-relay receives its inputs from requisite feeder.

The proposed relay is subjected to offline and online tests at different locations of the test bed. A summary of the online test results is presented in Tables 5 and 6. The offline test results are similar to the results of online tests presented in the Tables. In the Tables, t_f^- = pre-fault time, t_f = fault-on time, t_f^+ = post-fault time.

Figure 5 presents graphical display of parameters of the micro-source (P_{mn}, Q_{mn}, V_{an} and I_{mn}) during a three phase short circuit applied at terminals of MS1. The short circuit is applied at 30 s and withdrawn at 32 s, in islanded mode V control. Note that the sub-relay outputs logic 1 from 0 s to approximately 9 s due to the high starting current of the micro-source. This response is expected and indicates proper operation of a protective device. However, if this is undesirable (since desirability is a function of application) it can be avoided if a 10 s starting delay is modeled and connected to the micro-source sub-relay. Also, note that the sub-relay's response to the short circuit is logic 1 from 30 s to 32 s, with another oscillatory response from approximately 32 s to 33.5 s due to post-fault high currents occasioned by instability. After the short circuit, the sub-relay generates logic 0 to reclose requisite CB.

Figure 6 presents graphical display of parameters of the feeder (P_{fn}, Q_{fn}, V_{1n} and I_{2n}) during a three phase short circuit applied at terminals of feeder-a. The short circuit is applied at 30 s and withdrawn at 32 s, in islanded mode V control. Note that the sub-relay's pre-fault response is 0. Its response to the short circuit is logic 1 from 30 s to 32 s. After the short circuit, the sub-relay generates logic 0 to reclose requisite CB.

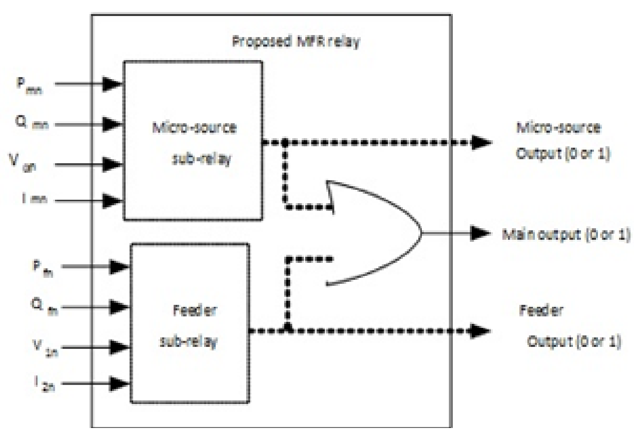


Figure 4. Block diagram showing inputs and output of the proposed relay.

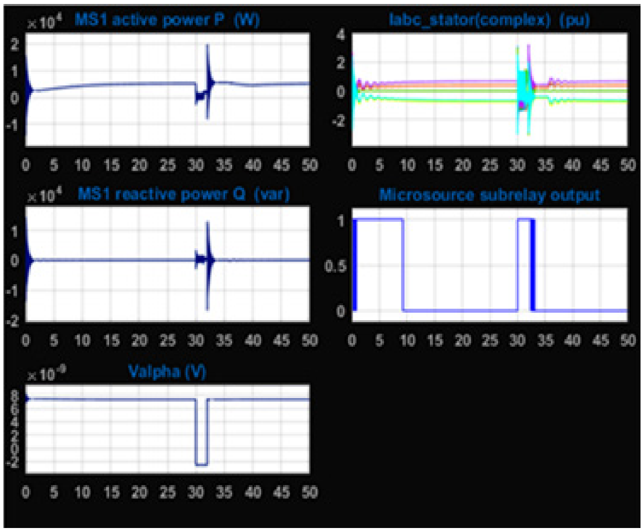


Figure 5. Graphical display of the critical parameters and sub-relay logic output for micro-source.

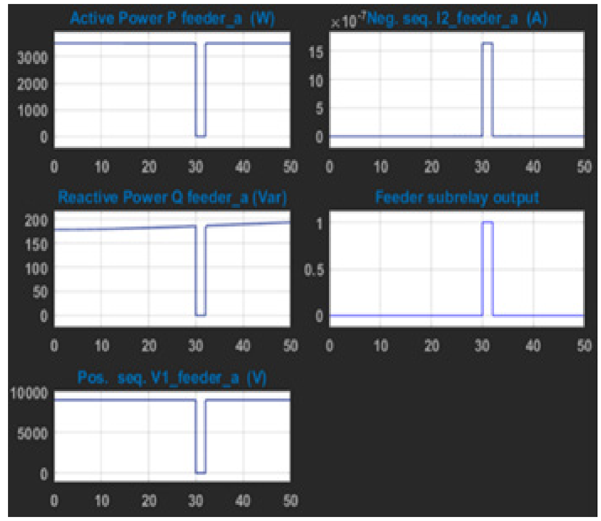


Figure 6. Graphical display of the critical parameters and sub-relay logic output for feeder.

Table 5. Logic response of MFR relay in grid-connected mod

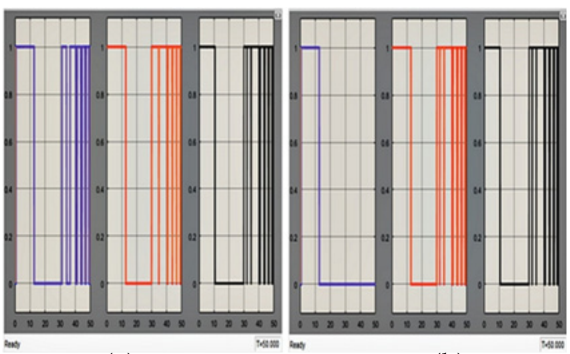
	Logic response of MFR relay					
	V control			Q control		
Nature of SC	t_f^-	t_f	t_f^+	t_f^-	t_f	t_f^+
$1-\varphi$	0	1	0	0	1	0
$L-L$	0	1	0	0	1	0
$3-\varphi$	0	1	0	0	1	0
$C-C$	0	1	0	0	1	0

Table 6. Major Parameters of the alternative test beds

	Test bed 2		Test bed 3		Test bed 4	
11.	**Utility**	**Micro-grid**	**Utility**	**Micro-grid**	**Utility**	**Micro-grid**
Generator voltage	Utility parameters of test bed 2 are same with utility parameters of the index test bed provided in Section 3.	-	16 kV	-	12 kV	-
Generated power		-	180 MVA	-	60 MVA	-
Transmission voltage		-	700 kV	-	132 kV	-
Transmission length		-	600 km	-	65 km	-
Micro-source voltage		400 V	-	800 V	-	575 V
Micro-source power		1.5 kW	-	30 kW	-	22 kW
Demand on micro-grid		1.2 kVA	-	24 kVA	-	18 kVA
Feeder voltage		6 kV	-	25 kV	-	11 kV
Feeder length		0.5 km	-	5.5 km	-	2.5 km

6. Response of Proposed MFR Relay Under Short Circuits

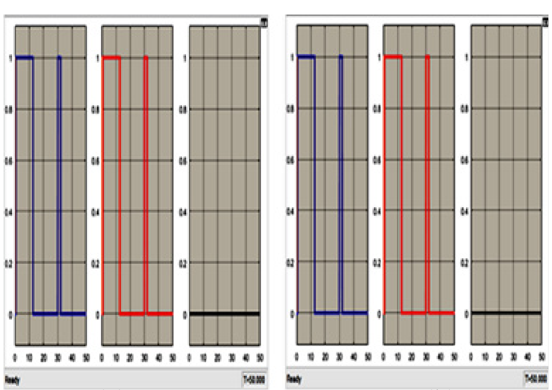
The response of proposed MFR relay to short circuit when embedded in the index test bed is presented in Figures 7-9. Short circuit is applied at 30.00 s and withdrawn at 32.00 s. In Figure 7 to Figure 9, sub-figure (a) displays response under V control while sub-figure (b) displays response under Q control. In either sub-figure, the blue trace in the left-hand-side shows response of the sub-relay linked to micro-source1. The red trace in the center shows response of proposed MFR relay to same short circuit, while the black trace in the right-hand-side shows response of sub-relay linked to feeder-a under same short circuit. The faults applied are single line-to-ground, line-to-line, three phase-to-ground and cross-country short circuits. Note that single line-to-ground short circuit is applied between phase A and neutral while line-to-line short circuit is applied between phases A and B. The proposed relay's response to short circuit is split into two: grid-connected responses and islanded responses.



(a) (b)

(a) V control; (b) Q control

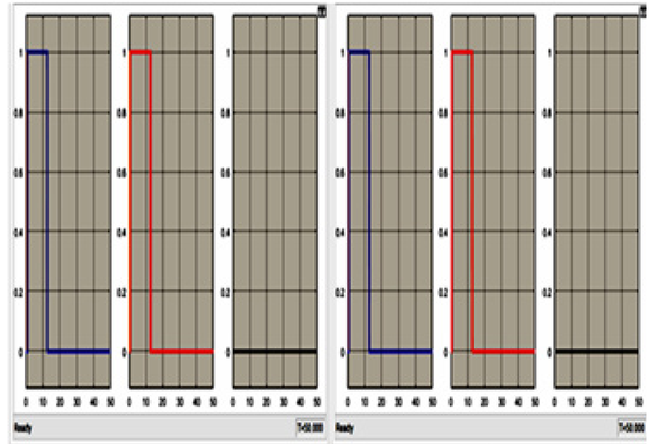
Figure 7. Utility generator terminals under L-G SC.



(a) (b)

(a) V control; (b) Q control

Figure 8. MS1 under L-G SC.



(a) (b)

(a) V control; (b) Q control

Figure 9. Feeder-b under three phase SC.

6.1 Grid-connected Responses

In the grid-connected mode, note that the sub-relays output logic 1 from 0 s to approximately 12 s in the micro-source sub-relay (and 10 s in the feeder sub-relay) due to the high starting current of the micro-source. This response is expected and indicates proper operation of a protective device. However, if this is undesirable (since desirability is a function of application) it can be avoided if a 10 s starting delay is modeled and connected to the micro-source sub-relays.

6.1.1 Utility Generator Terminals under L-G SC

Figure 7 presents, responses of MS1 sub-relay, proposed MFR relay and feeder-a sub-relay to single phase-to-ground short circuit applied at the terminals of utility generator in grid-connected mode under V and Q controls. In grid-connected mode, other short circuit conditions simulated are MS1 under L-L short circuit, MS2 under L-G short circuit, feeder-a under L-G short circuit, feeder-a under three phase short circuit, feeder-b under three phase short circuit.

6.2 Responses in Islanded Mode

Figures 8 and 9 present the responses of MS1 sub-relay, proposed MFR relay and feeder-a sub-relay to short circuits in both V and Q control strategies in islanded mode of operation. In both Figure 8 and 9, observe that the response of feeder-a sub-relay does not record the initial high starting current occasioned by starting of micro-sources (wind turbines) obtained in the grid-connected mode. This is a result of combination of the fact that micro-sources are not directly connected downstream of feeder-a (the position where feeder-a sub-relay is linked) on one hand, and the effect of high resistance of the feeder which is typical of distribution feeders, on the other hand. As obtainable in the grid-connected mode, sub-figure (a) shows response under V control while sub-figure (b) shows response under Q control. In both sub-figures, the blue trace in the left-hand-side represents response of MS1 sub-relay. The red trace in the center shows response of proposed MFR relay, while the black trace in the right-hand-side shows response of feeder-a sub-relay. Note also that virulent oscillations are not recorded during micro-grid short circuits in islanded mode largely due to comparatively smaller short circuit capacity of the system in islanded mode.

6.2.1 MS1 under L-G SC

Figure 8 presents response of MS1 sub-relay, proposed MFR relay and feeder-a sub-relay to single phase-to-ground short circuit in islanded mode under V and Q control strategies. The short circuit is applied at terminals of MS1.

6.2.2 Feeder-b under three phase SC

Figure 9 presents response of MS1 sub-relay, proposed MFR relay and feeder-a sub-relay to three phase-to-ground short circuits in islanded mode under V and Q control strategies. The short circuit is applied at terminals of feeder-b.

In islanded mode, other short circuit conditions simulated are MS1 under L-L short circuit, feeder-a under three phase short circuit, feeder-b under three phase short circuit, MS2 under three phase short circuit, micro-grid under cross-country three phase short circuit.

7. Alternative Test Beds

The proposed MFR relay is embedded in each of the three alternative test beds. The system under study is run for 50 s under normal operating conditions. The system is also run under short circuits. The pre-fault, fault-on and post-fault output logics of the proposed MFR relay are found to be similar to those of the index test bed as presented in Tables 5 and 6. In order to establish wide applicability of the proposed MFR relay model, three alternative test beds are developed. A summary of their parameters is provided in Table 6.

7.1 Response of Proposed MFR relay in Standard Test Beds

After establishing its response in the developed alternative test beds, the proposed relay is further embedded in each of 24 standard test beds. The standard test beds include the CERTS/AEP Test Bed and The IEEE European Low Voltage Test Feeders, excluding the effect of control strategies. The CERTS/AEP micro-grid test bed sought to enhance micro-sources into a micro-grid. In collaboration with AEP the project accomplished this objective through development and demonstration of three advanced techniques called the CERTS micro-grid concepts. The techniques are: 1. A method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2. A scheme of protection within the micro-grid that is devoid of high fault current; and 3. A method for micro-grid control which seeks to achieve voltage and frequency control in islanded mode without use of high-speed communication. The techniques were demonstrated at a full-scale test bed built near Columbus, Ohio and operated by AEP. Other participants in the project included University of Wisconsin-Madison, Sandia National Laboratories, Woodward, Princeton Power Systems, Northern Power Systems, Tecogen, and Lawrence Berkeley National Laboratory. The demonstration was sponsored by the California Energy Commission.

The relay performance is evaluated on the basis of the demerits associated with existing proposals. These demerits include drawbacks of using over current relays in micro-grids - such as blinding of protection and sympathetic tripping. The response of the proposed MFR relay is found to be devoid of the drawbacks associated with use of over current relays in micro-grids, specifically blinding of protection and sympathetic tripping.

8. Results and Discussion

In Figure 7, note that feeder-a sub-relay generates logic 0 during pre-fault, logic 1 during fault-on and logic 0 during post-fault, in both control strategies. Note also that due to high short circuit demand on MS1 its sub-relay produces logic 1 during fault-on and during post-fault in V control strategy. Observe the response of MS1 under Q control strategy – logic 0. Also observe the response of feeder-a in both control strategies. The responses under Q control strategy are consistent with design expectation.

This is because utility generator is located at the extreme end of the utility, far away from the PCC which is closer to the feeder sub-relay. The distance is accounted for by high impedance between the utility generator and MS1 sub-relay, resulting in passive response of MS1. However, due to proximate location of feeder-a sub-relay, it detects the short circuit in the utility. On one hand, this shows that MS1 sub-relay does not operate sympathetically under Q control. On another hand, it shows that feeder-a sub-relay is not blinded to the contribution of micro-grid to short circuit in the utility. This confirms that the proposed MFR relay exhibits capability for use in the unit scheme since feeder-a sub-relay detects abnormal flow of current and power occasioned by short circuit effect at the PCC.

Other short circuit conditions simulated with satisfactory responses are MS1 under L-L short circuit, MS2 under L-G short circuit, feeder-a under L-G short circuit, feeder-a under three phase short circuit, feeder-b under three phase short circuit.

In Figure 8, MS1 sub-relay produces logic 0 during pre-fault, logic 1 during fault-on and logic 0 during post-fault in both control strategies. This triggers the proposed MFR relay to trigger logic 1 only during single line-to-ground short circuit in both control strategies. As expected, the feeder sub-relay remains passive in both control strategies, indicative of selectivity required of a micro-grid protective system.

In Figure 9, both sub-relays produce passive response to the short circuit. This is because the short circuit is applied at adjacent feeder, indicating lack of sympathetic tripping by the proposed MFR relay as obtained in the grid-connected mode. This shows superior performance of the proposed MFR relay over proposals in literature that are based on use of over-current devices for micro-grid protection.

Other short circuit conditions simulated with satisfactory responses are MS1 under L-L short circuit, feeder-a under three phase short circuit, feeder-b under three phase short circuit, MS2 under three phase short circuit, micro-grid under cross-country three phase short circuit.

As shown in Figure7, a micro-source presents superior response to short circuit under Q control than under V control. This results in the superior performance of the proposed MFR relay under Q control strategy, a further confirmation that control strategies dictate system's characteristics as published in[28,29]. This is a major deficit in the proposals reported in literature, as they have been based on studies which ignore the effect of control on system's parameters.

As shown in Figure 8, when a micro-source experiences short circuit (L-G, or L-L or three phase), the affected micro-source sub-relay responds to its short circuit while associated feeder sub-relay is passive to the micro-source short circuit, an indication of selectivity of the proposed MFR relay to ensure minimal supply disruption as required by micro-grid protective system[30].

9. Conclusion

In this paper, a new protective relay has been developed and presented. Using a combination of requisite equations and extensive simulation of the test bed, the rules which engage four variables have been framed in fuzzy form. Using the framed rules, fuzzy logic controllers have been designed for micro-source and feeder sub-relays. The hardware has been realized using software combinational logic components, making it cost-effective. Offline and online response tests of the relay have been investigated and they show that it provides reliable detection and protection of the micro-grid against different short circuits in both islanded and grid-connected modes under both control regimes. It has been shown that the proposed relay does not suffer from blinding and sympathetic tripping. Its implementation facilitates the plug-and-play and peer-to-peer requirements of micro-grid protection, as presented in this paper.

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