Performance response tests on a new MFR relay for AC microgrids

***Abstract*—This paper presents the results of offline and online performance tests on a new multivariable fuzzy rule-based (MFR) relay for ac microgrids. The relay is based on measurement of four critical parameters (P, Q, V and I) and fuzzy logic implementation of rules framed on the basis of these parameters. The online test was performed by connecting the relay to a utility-microgrid testbed. The offline test was performed by simulating *High*, *Normal* and *Low* states of the critical parameters using proper combination of digital signal sources to implement short circuits (SCs) in SIMPOWERSystems®. In both offline and online tests, the faults simulated are standard SCs in the utility and microgrid. The results of both offline and online tests are similar, and show that the MFR relay outputs logic 1 during SC faults. The relay also outputs logic 0 before and after the SC faults for both offline and online tests.**

***Index Terms*—Distributed power generation, microgrids, power system fault, power system protection, smart grids.**

Nomenclature—MS1 = Microsource1, MS2 = Microsource2, t_f^- = pre-fault time, t_f = fault-on time, t_f^+ = post-fault time.

I. INTRODUCTION

Microgrids are a form of resilient distributed generation (DG) systems whose primary aim is provision of quality, reliable and sustainable power to a load center. A microgrid operates on advanced control structure and quality protection, and may include energy storage system, running autonomously or in grid-connected mode [1-4]. A microgrid is potentially beneficial to the consumer since a consumer could become a net producer. However, its deployment and operation suffer from disturbance-induced instability and design of protective systems [5-7]. Its full deployment implies increased penetration of renewable microsources at the distribution level. This alters the distribution system by making it active, resulting in loss of radial nature of the distribution system. This loss of radial nature of distribution network challenges over-current protective devices [8-10]. These challenges include:

- Blinding of protection.
- False tripping.
- Loss of fuse-recloser coordination.
- Non-synchronized reclosing.
- Disabling of automatic reclosing [11-13].

Efforts at solving these challenges have been documented in literature through proposals aimed at exploiting other parameters such as impedance, current differentials, adaptive techniques or addition of external devices during faults, as shown in Fig. 1 [14-16].

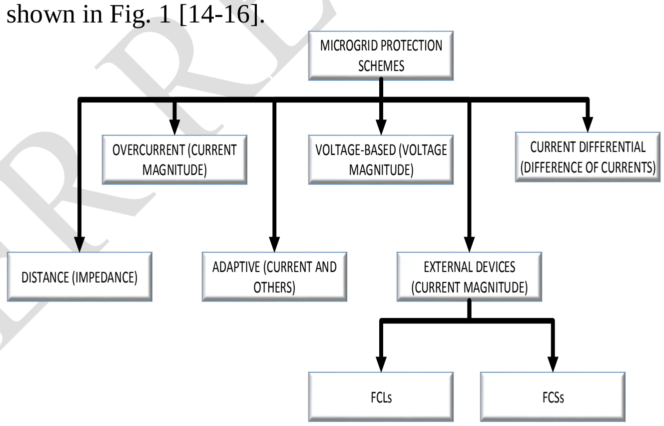

Fig. 1. Classification of protective schemes for microgrids.

While the solution to the challenges of using OC devices are provided in these proposals, other challenges are associated with them. Typically, current differential does not suffer from challenges of OC devices, it requires use of communication network. It is therefore vulnerable to communication failures in addition to failing plug-and-play requirement of microgrid. An example is the proposal by Dewadasa et. al. [17] in 2011 based on current differential. It potentially provides protection for the microgrid in both islanded and grid-connected modes but requires communication link. This makes it unreliable, in addition to possibility of error as penetration of DGs to the distribution network increases.

The use of external devices such as fault current limiters (FCLs) or fault current sources (FCSs) does not suffer from OC challenges however, the safety of the system and personnel during fault is potentially compromised by this system. An example is the proposal by Ustun et. al. [18] in 2011 which requires communication link and therefore vulnerable to link failure. In addition, it suffers from unreliable magnitude of FCL impedance magnitude due to the changes in impedance as a result of increased penetration of DG to the distribution network. Also, an error is introduced by the transient response of the added FCL impedance. Therefore, full deployment of microgrids necessitates having a new protective device which overcomes the challenges of OC and others reported in literature [15, 19].

This paper presents the results of offline and online performance tests on a new multivariable fuzzy rule-based (MFR) relay for ac microgrids. Modeled to the utility side of the system under study are synchronous generator, loads, STATCOM and transmission lines. The microgrid includes two doubly-fed induction generators, reactive var sources, loads and feeders.

II. DESIGN OF CONTROL SYSTEMS

The microgrid in the network developed is subjected to small signal analysis and established to be stable but recorded poor time response. Regulators are then designed to improve its response while retaining its stability using closed-loop feedback configuration. The regulators designed are pitch angle regulator, active power management systems and reactive power management systems. Thereafter, the testbed recorded satisfactory response and remains stable. By appropriately combining the regulators, two mutually exclusive control strategies were implemented. The strategies are active power-voltage (PV or simply V) and active-reactive power (PQ or simply Q) controls. When the testbed is studied under V control, the voltage controller ensures that the grid voltage remains stable with a 4% droop. When studied under Q control, the var controller ensures constant grid reactive power by either injecting or absorbing reactive power.

III. TESTBED VALIDATION USING SHORT CIRCUIT DYNAMIC ANALYSIS

Either of MS1 and MS2 of Fig. 2 has nominal rating of 5.5kW, 575V and connected to 2.5km highly resistive 11kV feeder (a or b). Each feeder is radially linked to the utility at the PCC. A 20MVA STATCOM is modeled and connected to the utility side at the PCC. The utility services a local inductive load of 3.6MVA and a remote inductive load of 89.44MVA, while the microgrid services total inductive local load of 6.21kVA. The system operates at 50Hz. The wind turbine is modeled to have cut-in and cut-out wind speeds of 3ms^{-1} and 6ms^{-1}, respectively.

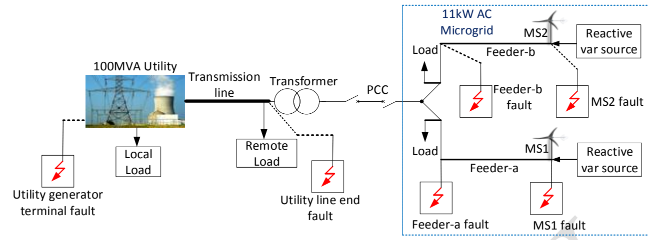

Fig. 2. A simple diagram showing basic elements of the system under study.

The developed testbed was validated using short circuit dynamic analysis under PV and PQ controls, in grid-connected and islanded operating modes. Validation was done for cross-country fault, utility fault, microsource fault and feeder fault under balanced 3-phase bolted SC, line-to-line SC and single line-to-ground SC. The response of microsource under normal condition is shown in Fig. 3. The response of microsource to balanced 3-phase SC at its terminals at 6 – 8 seconds under V control in islanded mode is depicted in Fig. 4a, while Fig. 4b shows same response to same SC under Q control in the same mode.

The 3-phase DFIG's complex stator voltage is transformed to a stationary dc reference frame using Clarke's transformation given in (1), as shown in Fig. 4a and Fig.4b, so as to simplify instrumentation. The validation confirm bidirectional power flow between utility and grid, and post-fault instability of microgrid, as published by Nikos Hatziargyriou in [20] and Amir Khaledian in [21]. It also confirms power management capability of DFIG as reported by Moayed Moghbel et. al. in [22] and in [23, 24]. The validations confirm that the response of the testbed is consistent with established SC theory.

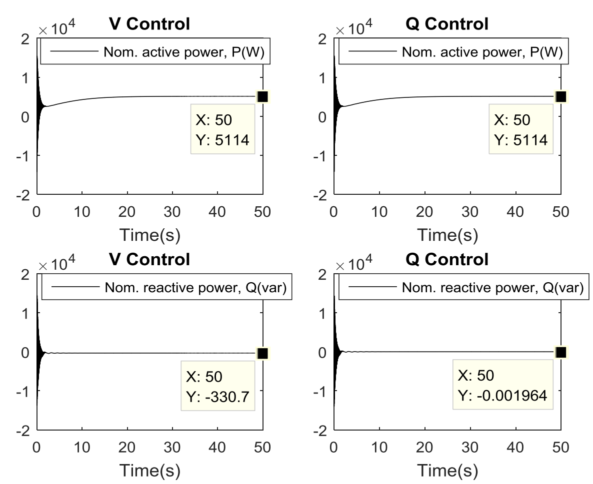

Fig. 3. Active and reactive power of microsources under fault-free condition.

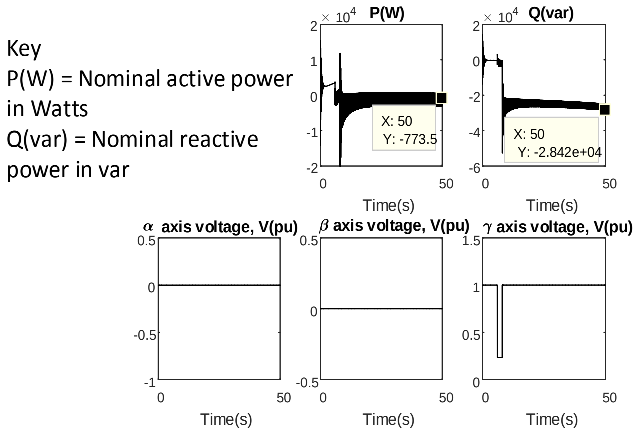

Fig. 4a**.** Response of MS1 to 3-phase bolted short circuit in islanded mode – V control.

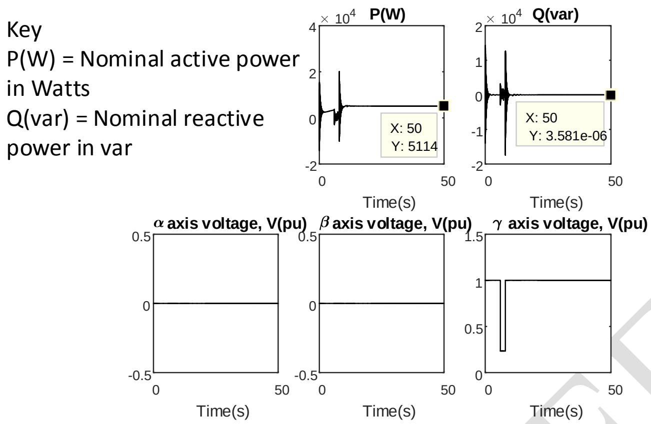

Fig. 4b**.** Response of MS1 to 3-phase bolted short circuit in islanded mode – Q control.

The $\alpha\beta\gamma$ transform applied to 3-phase voltage, as used by Edith Clarke, is presented in (1).

$$v_{\alpha\beta\gamma}(t) = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \quad (1)$$

Where,

$v_{\alpha\beta\gamma}(t)$ is a vector representing the α , β and γ components of the transformed voltage.

$v_a(t)$, $v_b(t)$ and $v_c(t)$ represent the A, B and C components of the feeder voltage in ABC reference frame.

IV. Multivariable Fuzzy Rule-Based Relay

A highlight of the input parameters of the proposed relay is provided as follows:

- Microsource
  - P_m = Nominal 3-phase active power from microsource, obtained by summing the 3-phase components via a summing circuit.
  - Q_m = A defined 3-phase reactive var of microsources 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.
- Feeder
  - P_f = 3-phase active power rating of the feeder.
  - Q_f = 3-phase reactive power rating of the feeder.
  - V_1 = Positive sequence feeder voltage.
  - I_2 = Negative sequence feeder current.

The hardware of the MFR relay, as proposed, was realized using software implementation of requisite fuzzy rules with combinational logic devices. The outputs of the two subrelays are combined using an OR gate, forming a composite relay for both microsource and feeder, as shown in Fig. 5.

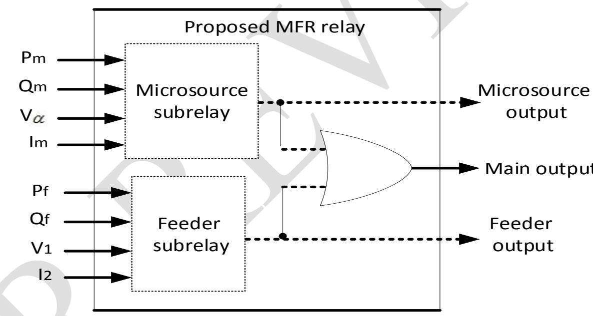

Fig. 5. Block diagram showing inputs and output of the proposed relay.

V. Connection Schemes

The MFR relay could be connected in two schemes, namely: the *unit* and *subunit* schemes. In the unit scheme, the outputs of the two subrelays are combined via an OR gate to output a single logic. This logic then controls a dedicated CB such as at the PCC. However, in the subunit scheme, the output of the MS subrelay controls a CB associated with output terminals of a microsource. Similarly, the output of the feeder subrelay controls a CB associated with a feeder. In both schemes, the MS subrelay receives inputs from its associated microsource while the feeder subrelay receives its inputs from appropriate feeder.

VI. Offline Test Network

Offline and online response tests were performed on the proposed relay at different locations of the testbed.

Fig. 6 and Fig. 7 depict simplified arrangements for the offline tests.

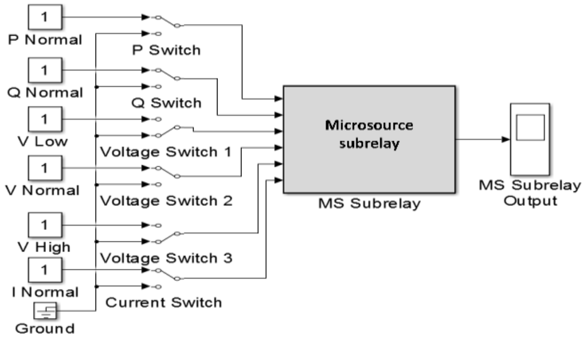

Fig. 6. A simplified arrangement for offline microsource subrelay test.

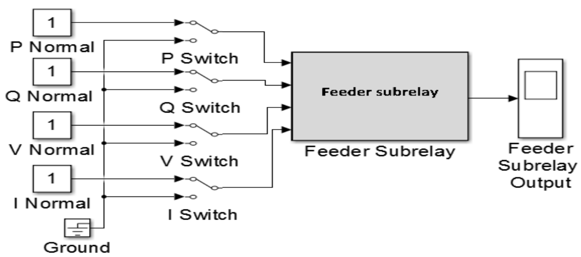

Fig. 7. A simplified arrangement for offline feeder subrelay test.

A summary of the offline test results for the MFR relay in *unit* scheme is presented in table I.

TABLE I LOGIC RESPONSE OF MFR RELAY FOR OFFLINE TEST

	Subunit scheme						**Unit scheme**		
	MS subrelay			Feeder subrelay					
Nature of SC	t_f^-	t_f	t_f^+	t_f^-	t_f	t_f^+	t_f^-	t_f	t_f^+
$1-\phi$	0	1	0	0	1	0	0	1	0
$L-L$	0	1	0	0	1	0	0	1	0
$3-\phi$	0	1	0	0	1	0	0	1	0
$C-C$	0	1	0	0	1	0	0	1	0

The offline test results are similar to the results of online tests presented in Fig. 8 and Fig. 9, except that voltage (V) and reactive power (Q) control strategies as well as islanding or grid-connection could not be simulated in the offline test.

VII. ONLINE TEST RESULTS

Fig. 8 and Fig. 9 provide graphical display of the critical parameters before, during and after 3-phase SC for both microsource and feeder subrelays in islanded mode. The output logics of the associated subrelays are also shown. The resnponse of the subrelay in islanded mode is similar to its response in grid-connected mode.

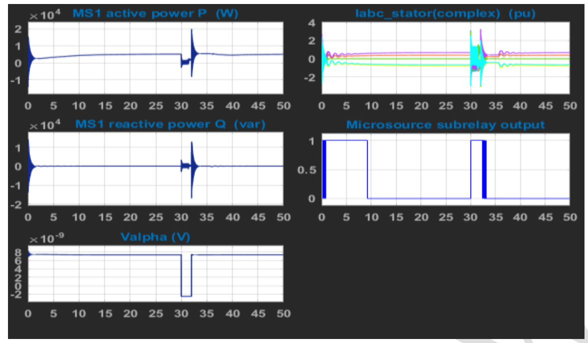

Fig. 8. Graphical display of the critical parameters and subrelay logic output for microsource in islanded mode.

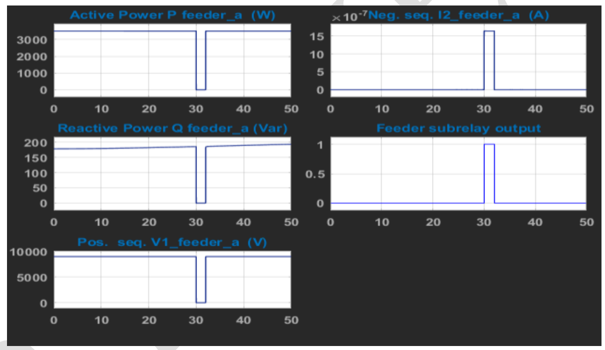

Fig. 9. Graphical display of the critical parameters and subrelay logic output for feeder.

VIII. RESULTS AND DISCUSSION

At 50.0s, under V control (Fig. 4a) when 3-phase bolted short circuit is applied at its terminals, MS1 absorbs 0.7735kW from MS2 and also absorbs 28.42kvar from its reactive var compensator and that of MS2. This is in contrast with Q control (Fig. 4b) where MS1 generates 5.114kW and supports the system with 3.581x10^{-6}var, indicative of reactive power management capability of DFIG as published by Moayed Moghbel et. al. in [22] and in [25-27]. This confirms the validity of the testbed.

In the simplified arrangement for offline microsource subrelay test shown in Fig. 6, the four critical parameters are in *Normal* states. Under this condition, the relay outputs a logic 0. For “Voltage Switch 1” (VS1), “Voltage Switch 2” (VS2) and “Voltage Switch 3” (VS3), only one of them is thrown to connect a unit signal to the MFR relay at any instant. In the present *Normal* condition when “V Normal” is applied to the relay, only VS2 is thrown to closed position while VS1 and VS3 remain in open position. Using similar concept, the system is in *abnormal* (fault) state when either VS1 or VS3 is thrown to connect “V Low” or “V High” to the relay. Under such condition, the relay outputs logic 1. Similarly, in the arrangement presented in Fig. 6, “P Switch”, “Q Switch” and “Current Switch” are in *Normal* positions. If any of these three switches is displaced and the model is run, the MFR relay outputs logic 0. Using the same approach, the simplified arrangement for the feeder subrelay presented in

Fig. 7 was also tested, yielding similar results as those obtained from microsource subrelay. The discussion in this paragraph is on the subunit scheme of the MFR relay in offline state.

Equivalent online tests were performed on the subunit scheme of the MFR relay and the results show that each subrelay outputs logic 1 during fault and logic 0 at pre- and post-fault. A graphical summary of the online test results for the MFR relay in subunit scheme is presented in Fig. 8 and Fig. 9.

IX. Conclusion

The challenges facing the current protective devices as well as proposed devices and the need for a new protective device have been summarized and presented in this paper. This work presents effort aimed at developing a utility-connected microgrid testbed. The utility model includes a synchronous generator, STATCOM, loads and transmission lines. The microgrid side includes two DFIGs as microsources, distribution feeders, loads and var compensators. The microgrid is equipped with V and Q control capabilities. The two connection schemes of the MFR relay have also been summarized in this paper. A summary of the testbed's response to standard short circuits has been investigated and presented in this paper. A novel MFR relay has been subjected to offline and online tests and a summary of the results in unit and subunit schemes have been articulated. Consequently, performance response tests on the new MFR relay have been achieved and the response has shown that the relay is reliable.

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