NOVEL TESTING ALGORITHM FOR BUSBAR PROTECTION SYSTEMS USING IEC 61850 AND ARTIFICIAL INTELLIGENCE TECHNIQUES

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ABSTRACT

This paper presents a novel testing algorithm for busbar protection systems using IEC 61850 and Adaptive Neural Fuzzy Inference System (ANFIS). The busbar protection system has very important role in any substation, so that, the testing algorithm for such systems must be reliable for any substation configuration. The conventional testing algorithms/procedures are like trial and error and depending on the human experience factor. So that, the paper presents an automated algorithm based on IEC 61850 and ANFIS that can be implemented in secondary injection test set to do a very accurate testing algorithm automatically to guarantee the accurate performance and get all testing results to evaluate the busbar protection system. The algorithm is tested on a typical substation configuration in Egypt to show the validity and effectiveness of the novel algorithm.

Index Terms – Busbar Protection testing and commissioning, IEC 61850, GOOSE, Sampled Values, Substation Automation, Secondary Injection Testing, Protection System Testing.

I. INTRODUCTION

Test and verification of a busbar protection for complex substation configurations with multiple busbars, bus couplers, bays and feeders has always been one of the most challenging tasks for commissioning process. A single test set, injecting currents at only a single CT location, does not provide enough confidence for the correct operation of the protection system. Using a simulation-based approach, where the whole busbar configurations with all its isolator configurations is modelled within a test set software, offers new possibilities for all fault scenarios which are important to verify, such as faults inside and outside the protected area or even faults in dead zones of the protection between a circuit breaker and its corresponding CTs. With a test set software, which can react to the individual circuit breaker trips with an iterative closed-loop simulation, the real behavior of the busbar protection, including breaker failure functions, can be seen. This can be achieved with multiple GPS time-synchronized test devices [1,4-10].

Modern digital busbar protection relays are a multifunctional device that contains main protection function, and additional functions, such as breaker failure and supervision, which also have to be considered in testing algorithm.

The main protection function of a busbar protection is a differential measurement. Due to the high requirements on speed and stability, modern busbar protection relays trip based on several separate measurements depended on the substation configuration and check zone, which is independent of any isolator state [4]. The differential measurements are usually stabilized with a percentage characteristic. When the differential measurements indicate a fault within a busbar zone, the busbar protection relay will utilize a trip logic which ensures that the fault is cleared selectively.

Focusing on how this has previously been tested will show up the limitations of current solutions and at the same time lead to the advantages of the novel algorithm depicted in this paper.

For testing a percentage differential characteristic [5], at least two currents have to be injected into the busbar protection to be able to simulate a fault current at the same time. Usually modern protection testing software supports this by visualizing the characteristic and calculating the currents based on a test point placed on the characteristic. For busbar differential protection this type of testing can have its limitations. As already described, a busbar protection can have multiple differential measurements, which can be set independently. In case they are active and

set differently, these differential measurements overlap.
Another challenge when testing the characteristic, or generally when injecting currents, arises when the busbar protection system is distributed and the bay units are separated by longer distances. Either very long test leads are needed or, if this is not possible, the test system has to operate several distributed test sets. To avoid an unintentional differential current while testing, the injected signals have to be time-synchronized over several test sets. Testing the characteristic of the check zone [3] requires the injection of three currents to be able to test the selection of the stabilizing current. Because of the limited amount of current outputs on the test sets, this is often achieved by looping the current through the bay units. However, because modern low impedance busbar differential relays support different current transformer ratios in every bay, this is not always possible.
Testing the tripping logic is often the most complex part of a busbar protection field test. Due to all the possible busbar configurations, almost every application of a busbar protection system is different. Thus there is no standard way of testing the trip logic. To determine the correct bays to trip and clear the fault, the busbar protection needs to know the exact topology of the busbar. Therefore, the busbar protection needs to know the connection scheme and check the isolator position for all feeders, sectionalizers and couplers during operation.
Several operating scenarios should be tested which depending on the human experience only that is meaning a limitation of the conventional testing algorithms/procedures.

In this paper, novel testing algorithm for busbar protection systems using IEC 61850 and Adaptive Neural Fuzzy Inference System (ANFIS) is implemented and tested. The algorithm receiving and transmitting the signals via Sampled Values (SVs) as a GOOSE messages on IEC 61850. Thus, all isolators' position and bus replica will be transmitted from protection relays or isolator racks to the test set via GOOSE messages. Then, the test set will run the Current Generator Algorithm (CGA) according to the connected bays and feeders, which in turn will generate the Injection Matrix (IM) that will be transmitted from test set to relays via SV GOOSE messages to be used in testing process. The pre-fault results that comprises the tripping decisions will also be transmitted back from protection relays to the test set via the SV GOOSE messages.

II. IEC61850 Based Substation Protection System

Firstly, the conventional substation configuration will be discussed in order to show the difference between conventional substations and IEC61850-based substations which requires a modern testing algorithm.
The conventional substation configuration are based on hardwired interface between the primary substation equipment, such as breakers, instrument transformers, transformers, etc. and the secondary protection and control devices [11-13]. A simplified diagram of the communication architecture of conventional substation is shown in Figure.1.
In the conventional substations, the CTs and VTs will transfer the analogue values or digital values to the interface module which includes both the analogue and digital input module through hardwires. After processing of the protection module, the output module will send control commands to other electrical equipment, such as trip a circuit breaker, also through hardwires. The Human Machine Interface (HMI) is directly installed in the protection relay in this strategy.
Considering the requirements for redundancy in protection functions, in conventional protection systems numerous primary and backup protection devices need to be installed, wired to the substation equipment.
The interface requirements of the relays are separate from these of the metering devices. As a result, they need their own instrument transformers which allow a wide dynamic range of fault currents.

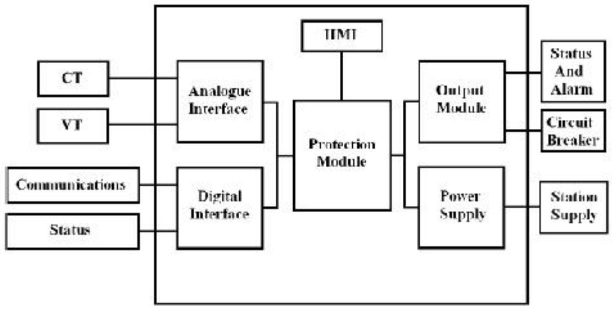

Figure 1: Communication architecture of a conventional substation protection system

By applying the IEC61850 base-substations [14-23], a significant improvement in functionality and reduction of the cost of integrated substation protection and control systems can be achieved. In these solutions, the interface of the instrument transformers which include both conventional and non-conventional ones with different types of substation protection, control, monitoring and recording equipment is through a Merging Unit. MUs could be physically located either in the field or in the control house.
It is very important to be able to interface with both the conventional and non- conventional sensors in order to allow the implementation of the system in both existing and new substations.
A simplified diagram of the communication architecture of an IEC61850 based substation protection system is shown in Figure.2. Also, Figure.3 shows Standard connection of MU at IEC61850 based substation protection system.

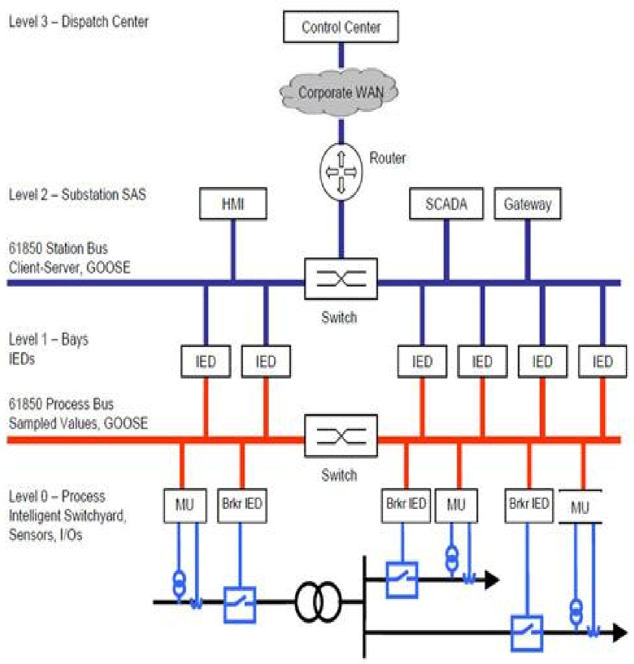

Figure 2: Communication architecture of an IEC61850 based substation protection system

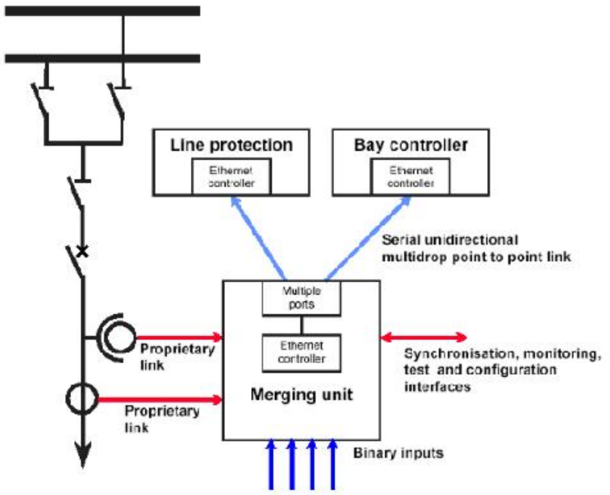

Figure 3: Standard connection of MU at IEC61850 based substation protection system

III. NOVEL TESTING ALGORITHM BASED IEC 61850 AND AI

According to the above description of the IEC 61850-Based substations, the testing and commissioning could be done via GOOSE Samples Values on the substation network and no need to conventional analogue signals and the complexity of the hard wires. Many manufacturers of secondary injection testers have developed the IEC 61850 facility on the test set e.g Omicron 256 Plus, HaoMAI Top Test, Kingsine K1066I, and ISA. The algorithm in the test set depends on the operator experience which leads in some cases to inaccurate or incomplete results and system evaluation. The novel algorithm presented in this paper is based on IEC 61850 communication protocol embedded with Artificial Intelligence technique which chosen to be the Adaptive Neuro-Fuzzy Inference System (ANFIS).

In this algorithm the IEC 61850 employed for further requirements than used with convention test sets as described on the start of this section. It is used to collect the dynamic bus replica or the isolator status –via SV GOOSE- from the ISO rack which collecting all status of isolators from the whole substation. Also, the current transformer ratio from all bays and bus coupler will be transferred to the algorithm via SV GOOSE to be used in the CGA and IM.

All the above data will be transferred to the novel testing algorithm via IEC 61850 to start generating the adequate IM as per substation configuration and testing case defined by the user through a pre-configured Fuzzy Inference System (FIS) according to the operation scenario of the substation. Figure.4 shows AI block that is used for CGA. That means the CGA is AI-based.

The IM values will be transferred back to the busbar protection system via SVs GOOSE to be processed by the protection relays and take the decision according to the injected currents equivalent to the generated IM.

All performed actions by the busbar protection system e.g. tripping, pickup, input contact status, output contact status, actual circuit breaker status…etc. will be transferred to the test set via SV GOOSE to evaluate the busbar protection system. Flowchart in Figure.5 depicts the novel testing algorithm.

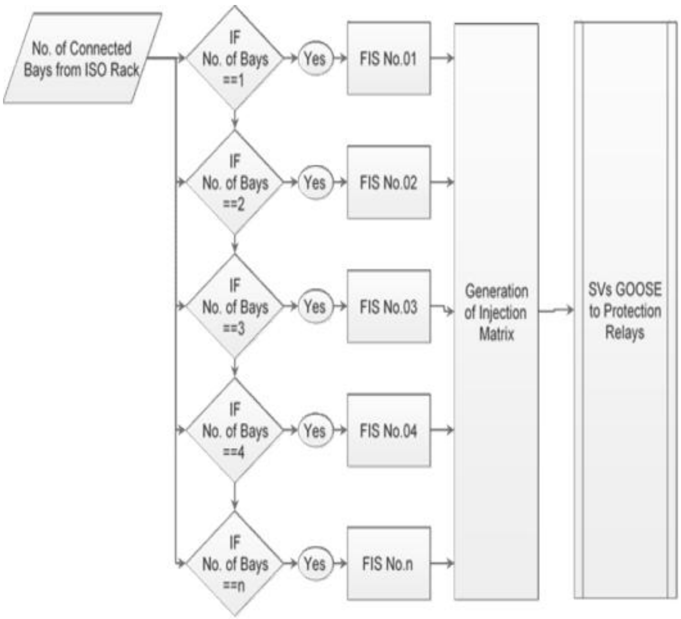

Figure 4: Flowchart of the current generator algorithm (CGA) that develops he per unit IM

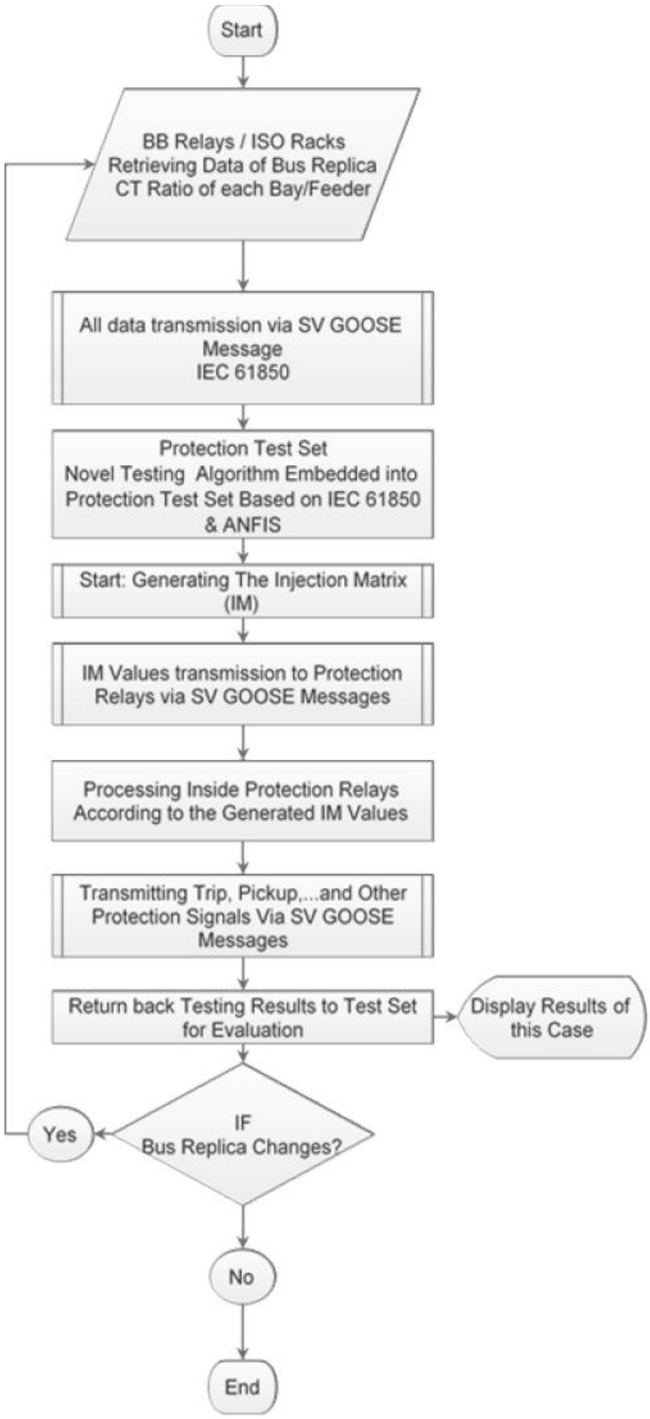

Figure 5: depicts the novel testing algorithm.

IV. TYPICAL SUBSTATION UNDER TESTING

Typical substation configuration in Egypt is chosen for testing the presented algorithm in this paper. The substation is 66/11kV, ten bays, four buses with four sectionalized isolators Q1-Q4, one coupler circuit breaker, and each bay is connected through two isolators that reflect the dynamic bus replica of the substation. Figure.6 depicts the substation configuration under testing to validate the new algorithm.

The busbar protection system is GE MULTILIN B90 comprises of six IEDs. IED 1, 2, and 3 is designated for protection of phase A, B, and C respectively as the system is considered phase segregated scheme. IED 4 is for collecting all isolator status for dynamic bus replica. IED 5 is for breakers failure for the whole substation. Finally, IED 6 is for end fault protection for faults at dead zones to trip the remote substation in case of outside fault. Figure.7 depicts the busbar protection system at the substation under test.

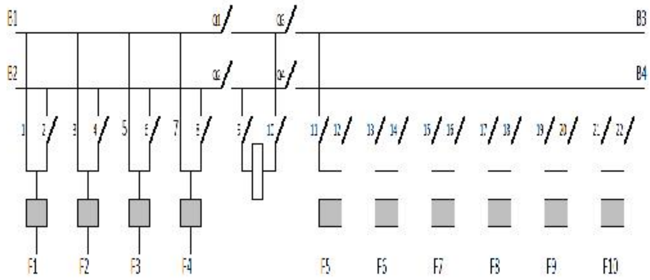

Figure 6: Typical substation 66/11kV as test system

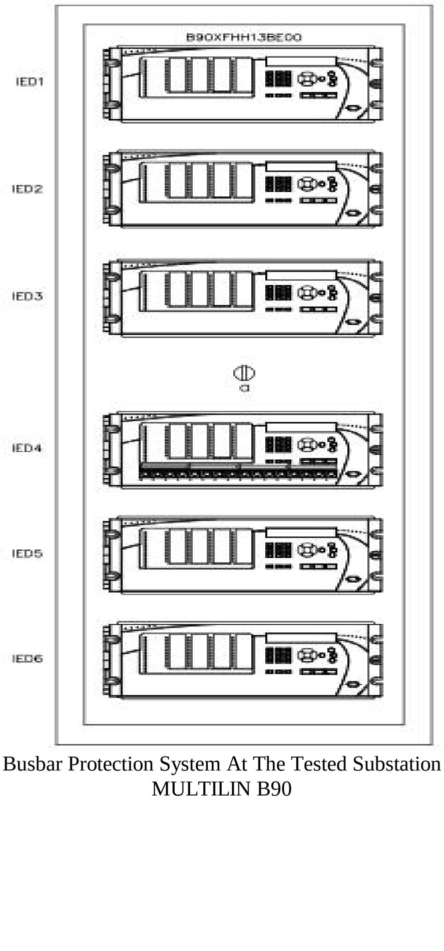

Figure 6: Busbar Protection System At The Tested Substation Type GE MULTILIN B90

CASE NO. 01: FOUR FEEDERS AT BUS 1

As shown in Figure.7, considering that four feeders are connected to bus 1 through closing the isolators 1, 3, 5, and 7. Hence, the protection zone will consider the four currents of the connected feeders. Considering that the first two feeders F1 and F2 are sources and F3 and F4 are loads. Also, assuming that equal supply and load sharing unless otherwise stated by the user. The above data will be transferred to the CGA via SVs GOOSE which in turn transferred to the adequate FIS structure to generate the IM values in per unit based on each current transformer rating. The algorithm is trained according to the following equations:

$$Is = \sum_{i=1}^{ns} F_i \quad (1)$$

$$I_{Li} = K \sum_{i=1}^{ns} F_i \quad (2)$$

Where;
Fi…..is the feeder number
Ns…..is the total number of source bays
K …..is the sharing factor

The IM values are generated as shown in Table.1 and transferred from the test set to the busbar protection system via SV GOOSE. The resulting trip matrix according to the behavior of the busbar protection system is received via SV GOOSE to check the performance of the system. All tripping cases are evaluated as per substation design and are found satisfactory as shown in Table.2.

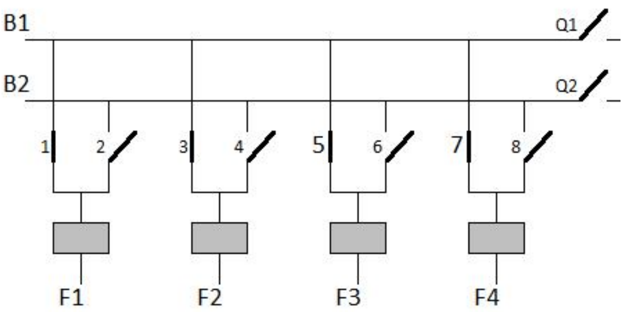

Figure 7: Single Line diagram of case No.01

Table 1: Injection Matrix for the case of four feeders at Bus1

Case	F1		F2		F3		F4	
No.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
1	1	0	1	0	0.4	180	1	180
2	1	0	1	0	0	0	1	180
3	1	0	0	0	0.4	180	1	180
4	0	0	1	0	0.4	180	1	180
5	1	0	1	0	0.4	0	1	180
6	1	0	1	0	0.4	180	1	0
7	1	0	1	0	0.4	0	1	0

Table 2: Expected trip matrix

Case No.	Differential Operate	Trip Operate
1	NO	NO
2	YES	YES
3	YES	YES
4	YES	YES
5	YES	YES
6	YES	YES
7	YES	YES

CASE NO. 02: TWO FEEDERS AT BUS 1 & TWO FEEDERS AT BUS 2 WITH BUS COUPLER IS CLOSED

As shown in Figure.8, according to the closing action of the bus coupler circuit breaker, Bus 1 and Bus 2 are considered the same protection zone. Hence, the protection zone will consider the four currents of the connected feeders. Thus, same IM and tripping results are obtained as Case No.01.

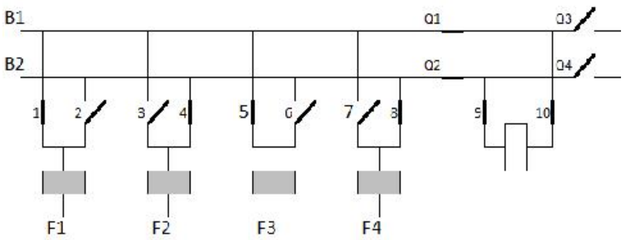

Figure 8: Single line diagram of case No. 2

CASE NO. 03: THREE FEEDERS AT BUS 1
ONE SOURCES AND TWO LOAD BAY

As shown in Figure.9, and by closing isolators 1, 3, and 5. Considering that F1 is source bay and F2 and F3 are load bays in this operation scenario. The IM values are generated as shown in Table.3 and transferred from the test set to the busbar protection system via SV GOOSE. The resulting trip matrix according to the behavior of the busbar protection system is received via SV GOOSE to check the performance of the system. All tripping cases are evaluated as per substation design and is found satisfactory as shown in Table.4.

Table 3: Injection Matrix for the case of three feeders at Bus1 One source and two loads

Case	F1		F2		F3	
No.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
1	2	0	1	180	0.4	180
2	2	0	1	180	0	0
3	2	0	0	0	0.4	180
4	0	0	1	180	0.4	180
5	2	0	1	180	0.4	0
6	2	0	1	0	0.4	180

Table 4: Expected trip matrix

Case No.	Differential Operate	Trip Operate
1	NO	NO
2	YES	YES
3	YES	YES
4	YES	YES
5	YES	YES
6	YES	YES

CASE NO. 04: THREE FEEDERS AT BUS 2 TWO SOURCES AND ONE LOAD BAY

As shown in Figure.8, and by closing isolators 2, 4, and 6. Considering that F1 AND F2 are source bays and F3 is load bays in this operation scenario. The IM values are generated as shown in Table.5 and transferred from the test set to the busbar protection system via SV GOOSE. The resulting trip matrix according to the behavior of the busbar protection system is received via SV GOOSE to check the performance of the system. All tripping cases are evaluated as per substation design and is found satisfactory as shown in Table.6.

Table 5: Injection Matrix for the case of three feeders at Bus1 Two sources and one load

Case	F1		F2		F3	
No.	Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
1	1	0	1	0	0.8	180
2	1	0	1	0	0	0
3	1	0	0	0	0.8	180
4	0	0	1	0	0.8	180
5	1	0	1	0	0.8	180

Table 6: Expected trip matrix

Case No.	Differential Operate	Trip Operate
1	NO	NO
2	YES	YES
3	YES	YES
4	YES	YES
5	YES	YES

CASE NO. 05: STABILITY TEST FOR THE WHOLE SUBSTATION

The above comprehensive analysis through the practical testing for the busbar protection system proves the validity and effectiveness of the presented testing algorithm in this paper. Thus, this section will present a detailed stability testing for the whole substation –shown in Figure.6- using the IEC 61850 and the CGA. The testing will show the busbar protection system evaluation in both stable operation scenarios and fault (unstable) cases for the whole protection zones and check zone of the B90 busbar protection system. Refer to Table.7 that shows the IEC 61850 evaluation sheet for this testing type.

CASE NO. 06: BREAKERS FAILURE TEST FOR THE WHOLE SUBSTATION

The novel algorithm presented in this paper is also capable to evaluate the performance of the substation breakers failure protection schemes embedded into the busbar protection system at IED 5 as described before.

The IM generated from CGA according to the retrieved settings values of current threshold and breakers failure first stage time (BF1) and Breaker Failure second stage time (BF2) through SV GOOSE messages from the protection system. Then, the IEC 65850 evaluation sheet is retrieved with the IM values and time response for BF1 and BF2. Also, the actual threshold values for each bay as indicated in Table.8

Table 7: IEC 61850 evaluation sheet during testing with the IM values generated by the CGA for stability test

Stability Test Differential and Restrain Test													
IM per unit values generated by CGA								Stable Case		Check Zone		Unstable Case by reversing I2	
CT IED 1,2,3	CT IED 4,5,6	Bay ID	CT Ratio	Q 1	Q 2	I1 (A)	I2 (A)	Id	Ir	Id	Ir	Id	Ir
F1	N/A	P1 (F01)	800	C	O	0.25<0		Reference					
F2	N/A	P2 (F02)	800	C	O		0.25 <180	9	196	9	196	396	196
F3	N/A	P3 (F03)	2000	C	O		0.1 <180	6	200	6	200	391	196
F4	N/A	P4 (F04)	800	C	O		0.25 <180	6	196	6	196	397	196
F5	F1	P5 (F05)	800	C	O		0.25 <180	7	196	7	196	398	196
F6	F2	P6 (F06)	600	C	O		0.33 <180	3	200	3	200	396	196
F7	F3	P7 (BC)	2500	C	O		0.08 <0	14	196	14	196	388	196
F8	F4	P8 (BC)	2500	C	O		0.08 <0	16	196	16	196	380	196
L1	F5	P9 (F08)	600	C	O		0.33 <180	7	196	7	196	386	196
L2	F6	P10 (F09)	800	C	O		0.25 <180	15	196	15	196	392	196

Table 8: IEC 61850 evaluation sheet during testing with the IM values generated by the CGA for breaker failure test

	Bus Connected		Current Threshold (A)	Injected Current (A)			BF 1 (ms)	BF 2 (ms)	Remarks
	B1	B2			3-Ph Init	SF6			
Bay 1	X		0.4	0.41	Ok	Ok	151	255	B1 Trips
Bay 2		X	0.4	0.41	Ok	Ok	150	256	B2 Trips
Bay 3		X	0.133	0.14	Ok	Ok	149	251	B2 Trips
Bay 4		X	0.133	0.14	Ok	Ok	151	253	B2 Trips
Bay 5/6 Coupler	Closed		0.5	0.51	0.5	Ok	155	255	
	B3	B4							
Bay 7	X		0.4	0.41	Ok	Ok	152	256	B1 Trips
Bay 8		X	0.4	0.41	Ok	Ok	153	258	B2 Trips
Bay 9		X	0.133	0.14	Ok	Ok	151	254	B2 Trips
Bay 10		X	0.4	0.41	Ok	Ok	152	253	B2 Trips
Bay 11	X		0.4	0.41	Ok	Ok	150	251	B1 Trips
Bay 12		X	0.4	0.41	Ok	Ok	151	254	B2 Trips

V. CONCLUSION

The paper presents an automated and adaptive testing algorithm based on IEC 61850 and ANFIS that can be implemented in secondary injection test set to do a very accurate testing algorithm automatically to guarantee the accurate performance of the busbar protection system and get all testing results to evaluate the busbar protection system. The algorithm is tested on a typical 66/11 kV substation configuration in Egypt with ten bays to show the validity and effectiveness of the novel algorithm. The busbar protection system is tested for several cases under different operation scenarios proving the validity of the novel algorithm in testing such substations. The novel algorithm show its validity also in testing and evaluating the breakers failure protection system embedded into the busbar protection system. After all analysis and practical testing presented in this paper, it is recommended to develop a software package to be implemented into the secondary injection test set by implementing this novel algorithm to do easy, accurate, reliable testing and commissioning for the busbar protection system.

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BIOGRAPHY

Mohamed A. Ali was born in 1982. He received the B.Sc., M.Sc., and PhD degree in electrical engineering from Zagazig University, and Benha University, Egypt, respectively. His practical experience included the power system protection systems up to the 500kV level with the application on the Egyptian electrical grid and the standard testing systems for all protection schemes of traditional and IEC 61850 substations and power plants. His research interests are power system analysis, stability, control and protection. He published several researches regarding the mentioned interests in many international journals and conferences. He interested with international research projects.