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Performance of out-of-step tripping protection under renewable integration

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Gaoyuan Liu[1] ✉, *Sadegh Azizi*[1], *Mingyu Sun*[1], *Marjan Popov*[2], *Vladimir Terzija*[1]

[1]*School of Electrical and Electronic Engineering, University of Manchester, Manchester, England, UK*

[2]*Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Delft, The Netherlands*

✉ *E-mail: gaoyuan.liu@outlook.com*

Abstract: In future power systems, highly increased renewable integration is expected to meet global decarbonisation targets. The risks and uncertainties brought about by renewable integration will challenge system stability. This study analyses the impact of the increased level of renewable energy sources integration on system transient stability and out-of-step tripping (OST) protection. To this end, the performance of OST protection is assessed in terms of the ability to prevent system instability under different contingencies. A modified two-area test system and Great Britain (GB) 29-zone system integrated with a dynamic model of wind turbines are selected as test systems. A systematic approach is adopted to design a specific OST protection scheme for each test system and to obtain suitable relay settings. An extensive number of simulation studies are carried out using DIgSILENT PowerFactory to assess the performance of the designed schemes under different renewable integration levels. Conclusions are made based on the obtained results, which all imply that revision of the existing OST protection scheme will be inevitably needed.

1 Introduction

The development of renewable generation technologies has progressed rapidly around the world over the recent years, facilitating large-scale deployment and integration of renewable energy sources (RES) in power systems. This dramatic change in power generation sector brings challenges and uncertainties to the stability of power systems.

Out-of-step tripping (OST) protection falls under System Integrity Protection Schemes. It is designed, in principle, to separate a power system into isolated islands following severe disturbances, as a last resort to prevent wide-area blackouts [1]. Out-of-step or loss of synchronism condition occurs when one or a number of generators in the system fail to maintain synchronism with the rest of generators. OST protection is achieved by installing relays that are equipped to detect out-of-step conditions. A number of techniques that can be used to detect out-of-step condition exist both in literature and in practice. The impedance-based out-of-step detection method is a conventional and widely used technique. Other newly developed detection methods include swing-centre voltage (SCV)-based technique, synchrophasor-based technique and equal area criterion-based technique [2, 3]. However, these proposed techniques in literature need additional input parameters and high-speed communication media to achieve fast out-of-step detection. The impedance-based detection method is well established and its long-term service in practice has been proven to be reliable and effective [2]. Thus, this paper focuses on the impedance-based detection method.

One of the biggest challenges brought by large-scale renewable integration is reduced system inertia. With a displacement of conventional synchronously connected generators, the system inertia time constant decreases dramatically [4]. In addition, the system inertia becomes time-varying due to the constant change of power injection from RES. Low inertia systems may lose their transient stability more easily in the event of severe disturbances. Controlled system separation by OST protection, as the last defence against blackouts, is becoming more important and necessary for such low inertia systems. However, it is unknown how the operation of OST protection will be affected by increasing penetration of RES. In [5], sensitivity analysis shows that changes in system inertia can interfere with the coherency of generator groups, which may change generator grouping and thus separation boundaries. Centeno *et al.* [6] pointed out that the system inertia time constant is an important input of OST relay settings. Reduced inertia time constant can lead to larger swing frequency and rate of change of apparent impedance measured by OST relays. However, there is no thorough investigation into the performance of traditional OST relays under reduced and time-varying system inertia time constant in literature.

This paper tries to assess the performance of OST protection under renewable integration. The aim of the investigation is to identify the constraints and shortcomings of the traditional impedance-based OST scheme. The study is carried out on a modified two-area test system and a Great Britain (GB) 29-zone test system. Stability studies, as the most effective method to design the OST scheme, are conducted for each system [7, 8]. After setting relays in each system, simulations are carried out to test the designed schemes under various RES penetration levels in that system. In total, over 25,000 time-domain simulations are conducted. A number of important conclusions are made based on simulation results, which suggests that a thorough revision of the existing impedance-based OST scheme is needed.

2 Impedance-based OST protection

The impedance-based out-of-step detection method is based on the fact that the positive-sequence impedance measured by the distance relay changes due to fluctuations of voltages and currents during a power swing. This phenomenon can be explained using a simple two-source system as follows.

A two-source system is shown in Fig. 1, consisting of two generators connected by a transmission line. The internal voltage of two generators is $E_S\angle\delta$ and $E_R\angle 0°$, respectively. The impedance of the two generators and the transmission line is denoted by Z_S, Z_R and Z_L, respectively. The positive-sequence impedance measured at the sending-end of the line can be expressed as explained below. The current flowing from the sending end of the line towards its receiving end can be calculated as

$$I_1 = \frac{E_S\angle\delta - E_R}{Z_T} \quad (1)$$

where Z_T is the system total impedance.

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The sending-end voltage can be expressed as

$$V_S = E_S\angle\delta - Z_S I_1 \tag{2}$$

The positive-sequence impedance measured at the sending end is

$$Z_1 = \frac{V_S}{I_1} = \frac{E_S\angle\delta}{E_S\angle\delta - E_R} Z_T - Z_S \tag{3}$$

Assuming $E_S = E_R$, the above equation can be simplified as

$$Z_1 = \left(\frac{Z_T}{2} - Z_S\right) - j\left(\frac{Z_T}{2}\cot\left(\frac{\delta}{2}\right)\right) \tag{4}$$

The positive-sequence impedance measured at the sending end of the line forms a trajectory in the resistance–reactance (R–X) plane when δ changes from 0° to 360°, as shown in Fig. 2.

The trajectory is a straight line that is orthogonal to Z_T when $E_S = E_R$ and follows a circle if $E_S \neq E_R$. Practically speaking, an out-of-step condition is declared when δ reaches 180°.

In order to detect the out-of-step condition, OST relays that are equipped with special characteristics are used. A number of characteristic elements have been used in practice, including concentric polygons and concentric circles as shown in Fig. 3 [9].

Impedance-based OST relays distinguish power swings from faults based on the fact that power swings are electromechanical transients and slower than faults that are electromagnetic transients. A timer is used to record the dwelling time spent by the impedance trajectory travelling between the outer and the inner zone of the relay characteristics. The relay declares a power swing if the dwelling time is longer than a threshold. In addition to relay settings, it is important to place OST relays at optimal locations to facilitate out-of-step detection. The electrical centre of the system is considered the best location for placing OST relays [2]. However, stability studies must be carried out to choose the optimal location because the electrical centre is constantly changing under different operating conditions.

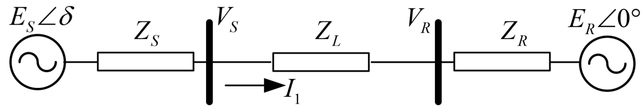

Fig. 1 *Two-source system*

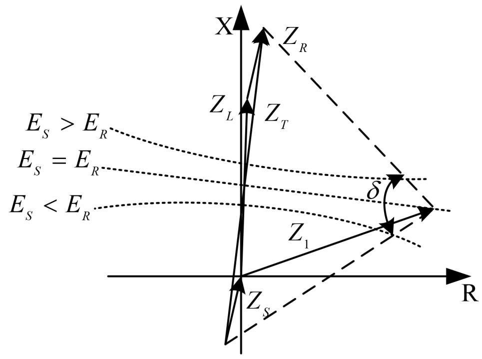

Fig. 2 *Impedance loci during out-of-step conditions [1]*

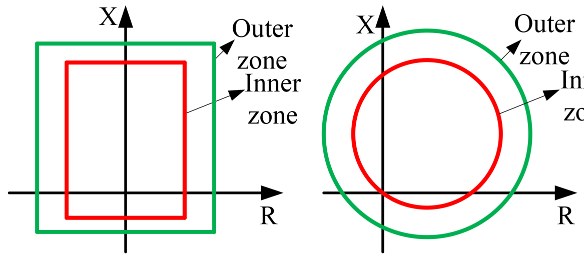

Fig. 3 *Typical OST relay characteristics [9]*

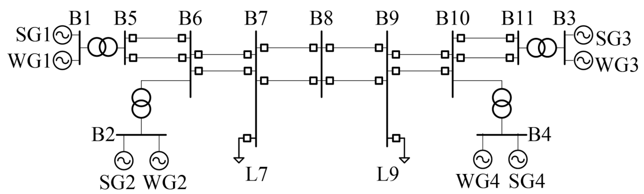

Fig. 4 *Modified two-area test system*

3 Test systems and testing protocols

3.1 Test systems

A modified two-area test system as shown in Fig. 4 is used to obtain general patterns about how the performance of OST protection is affected by renewable integration.

In doing so, the original Kundur's two-area system [10] is modified to include dynamic models of Type 4 wind generator (WG) in all generation buses. The total generation capacity in each generation bus remains unchanged. In this paper, a renewable penetration level is defined as the ratio between active power production by WGs and system's total power generation. The active power output of both synchronous generators (SGs) and WGs is appropriately changed to achieve desirable penetration level. Moreover, the rating of SGs is reduced accordingly to model the displacement of conventional generators when penetration level increases. All single-circuit transmission lines are replaced by double-circuit lines without changing the impedance of corresponding transmission paths. This is to make the system more secure and realistic, so that fault clearance by tripping a faulted line does not result in loss of a generation unit.

To validate general patterns obtained from the two-area test system, a more complex GB 29-zone system is used. The 29-zone system is developed in [11]. It consists of four subsystems with each of them representing the GB grid system at present, and in 2020, 2025 and 2030 horizon years, respectively. Fig. 5 shows the schematic diagram of the 29-zone system.

In this system, 29 zones are interconnected with transmission lines. Each zone consists of aggregated SGs, WGs and loads. The total installed WG capacity in each horizon year is in line with National Grid's prediction of future wind deployment as set out in Electricity Ten Year Statement [12]. The renewable penetration level as defined earlier is obtained to be 17%, 34%, 63% and 78% for each horizon year, respectively.

3.2 Testing protocols

A set of testing protocols are proposed to standardise procedures followed and indicators used to assess the performance of impedance-based OST protection schemes under renewable integration.

The first step is to design separation plan and OST relay settings for each system under presumed penetration level (PPL). Separation plan includes details about the placement of OST relays and separation boundaries. In this respect, time-domain simulations involving different types (balanced and unbalanced) of faults at different locations (beginning, middle and end of each line) with different fault clearing time (0.1, 0.2, …, 1 s) are carried out. A stable swing occurs when the fault is cleared before critical clearing time (CCT). Fault clearance after CCT will cause an unstable swing. During an unstable swing, coherent groups of generators can be identified by monitoring changes of generators' rotor angles. Between these coherent groups lies the optimal separation boundary. However, the balance between power generation and consumption in each created island should also be considered when determining exact separation boundaries.

In this study, one or more OST relays are installed on the boundary lines specified to detect loss of synchronism. The apparent impedance seen at the relay locations during each simulation case, either stable or unstable, is recorded for OST relay settings. The outer and inner zones of each relay are set according to all impedance trajectories obtained offline.

The OST schemes designed for each system at each PPL are then tested under different actual penetration levels (APLs). The dynamic model of OST relay is developed in DIgSILENT

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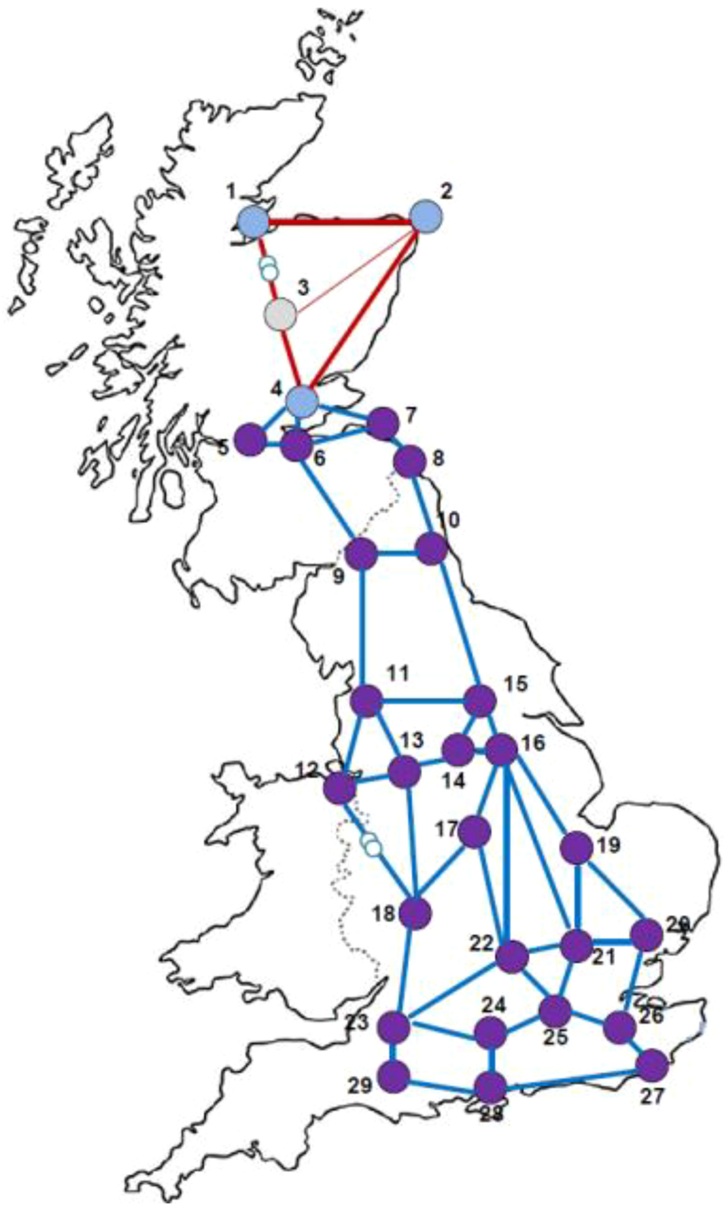

Fig. 5 *Schematic diagram of GB 29-zone system [11]*

PowerFactory. The relay is capable of extracting phasor from sampled voltage and current waveforms taken at the relay location. Impedance is then calculated and used for out-of-step detection. Tripping signals will be sent to lines on separation boundaries when out-of-step is detected.

Status of circuit breakers of preselected lines is monitored to record success/failure of separation and its time (if applicable). Rotor angles of generators are also recorded to determine if the transient stability of the system recovers after separation. All simulation cases are characterised into four categories: no operation and unwanted operation during a stable swing, and successful operation and missing operation during an unstable swing. The success rate is defined as the ratio between the number of cases where the system is separated as expected and the number of unstable cases.

4 Simulation results

To evaluate the performance of OST protection under different levels of renewable integration, numerous simulations are carried out in DIgSILENT PowerFactory. This section summarises the results obtained from both the modified two-area system and the GB 29-zone system.

4.1 Results on modified two-area system

In the modified two-area system, four renewable penetration levels are considered, being 0%, 25%, 50% and 75%, respectively. Therefore, four different sets of OST scheme design are required. The two-area system is frequently used to study inter-area oscillations because its symmetrical design essentially results in two areas. Generators on the left will swing against generators on the right during power swings. The transmission lines interconnecting these two areas are the best location for out-of-step detection. The reason is that such lines lie on the boundary between the two areas, as will be confirmed later by simulations. The separation plan is also very clear, i.e. tripping two tie-lines between B7 and B8 (or B8 and B9).

Average fault CCT for faults on each transmission line in the modified two-area system under different penetration levels is tabulated in Table 1.

It can be concluded from Table 1 that fault CCT decreases as penetration level increases. Under high renewable penetration levels, the system is more prone to instability if faults are not cleared fast enough.

Impedance loci seen at relay location in all simulation cases are plotted together to determine relay characteristics. Fig. 6 shows an example of a relay setting when PPL is 0%. Table 2 tabulates relay settings for all PPLs.

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Table 1 Fault CCT under different penetration levels

Penetration level, %	0	25	50	75
Line	Average CCT, s			
5-6	0.55	0.45	0.42	0.3
6-7	0.3	0.28	0.18	0.15
7-8	0.62	0.58	0.52	0.37
8-9	0.73	0.7	0.6	0.5
9-10	0.73	0.67	0.48	0.43
10-11	0.6	0.57	0.53	0.52

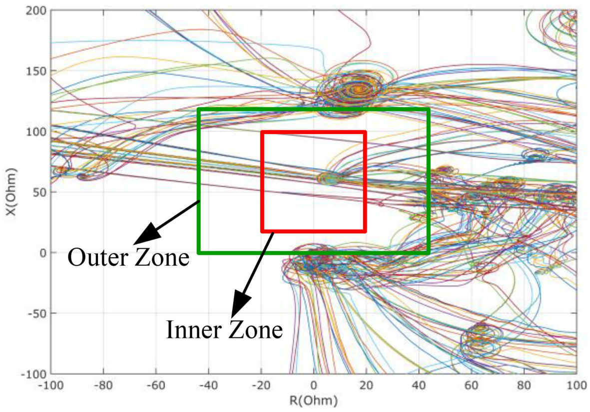

Fig. 6 *Impedance loci and OST relay characteristics*

Table 2 Relay settings for the modified two-area system

PPL, %	Inner blinder, Ω	Outer blinder, Ω	Upper boundary, Ω	Lower boundary, Ω	Time delay, ms
0	22	44	120	0	25
25	25	50	120	0	20
50	10	20	120	0	5
75	17	34	120	0	5

Table 3 Relay performance in the two-area system

APL, %	PPL, %	No. of unwanted separations	No. of missing separations	Success rate, %
0	0	0	0	100
	25	1	2	98.5
	50	0	2	98.5
	75	0	2	98.5
25	0	0	1	99
	25	0	0	100
	50	0	0	100
	75	1	0	99
50	0	3	5	97.2
	25	4	2	98.9
	50	0	0	100
	75	1	4	97.8
75	0	2	25	88.4
	25	4	16	92.6
	50	1	9	95.8
	75	0	0	100

For each system configured with different APLs, four sets of OST relay settings are tested. Results are tabulated in Table 3. It can be seen that the designed OST scheme performs perfectly with 100% success rate when APL equals PPL. This is expected because the scheme is specifically designed for a system with PPL. The success rate decreases when the designed scheme is applied to systems with APLs other than PPL. Both unwanted operations during stable swings and missing operation during unstable swings occur. Transient stability cannot be recovered in these cases. The results show that increasing renewable penetration level can have negative impacts on conventional impedance-based OST protection. In addition, its performance is also compromised when it is operated under lower penetration levels than presumed. Such condition exists in practice when renewable generation reduces its output due to either unit commitment or weather conditions.

Figs. 7 and 8 show the impedance trajectories recorded during two cases where the proposed OST scheme fails when APL is not equal to PPL. In Fig. 7, the relay malfunctions during a stable swing because impedance loci encroach on the relay's inner zone. Increased swing frequency due to reduced inertia causes the impedance locus to move further into characteristics within the same period of time. This misoperation is also partly due to the

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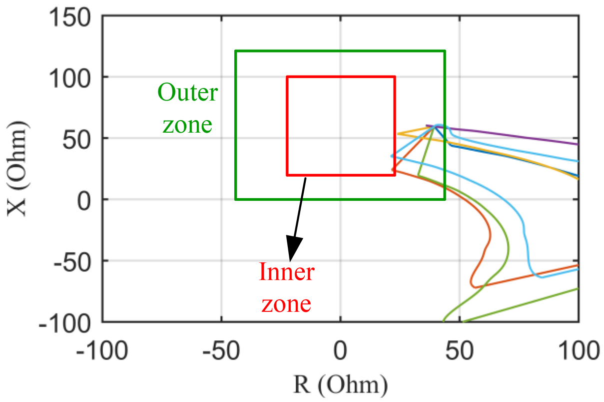

Fig. 7 *Unwanted operation during a stable swing*

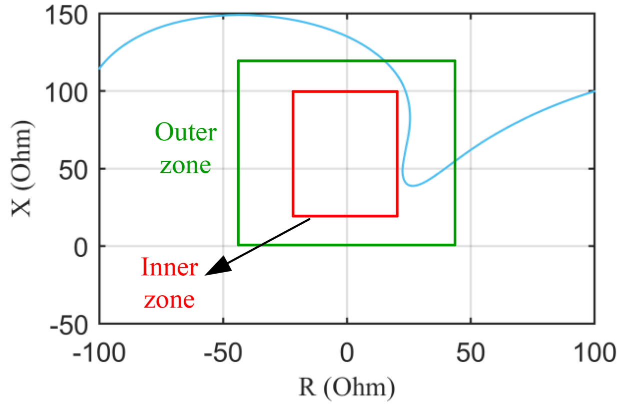

Fig. 8 *Missing operation during an unstable swing*

Table 4 Separation plan for GB 29-zone system

Year	Pattern	Relay location	Created islands	Separation points
present	1	2-4, 3-4	1-3|4-29	2-4, 3-4
	2	4-6, 4-7	1-4|5-29	4-5, 4-6, 4-7
	3	4-7, 6-7	1-6|7-29	4-7, 6-7, 6-9
	4	8-10, 9-10	1-9|10-29	8-10, 9-10, 9-11
	5	6-7, 8-10	1-4, 7, 8|5, 6, 9-29	4-5, 4-6, 6-7, 8-10
	6	17-22, 18-23	1-19|20-29	18-23, 17-22, 16-22, 16-21, 19-21, 19-20
2020	1	4-7, 5-6	1-5|6-29	4-6, 4-7, 5-6
	2	8-10, 9-10	1-9|10-29	8-10, 9-10, 9-11
2025	1	6-9, 8-10	1-8|9-29	6-9, 8-10
2030	1	6-9, 8-10	1-8|9-29	6-9, 8-10

Trip-on-the-way-in (TOWI) logic used in the scheme design, so that the relay trips once locus enters the inner zone. Using the Trip-on-the-way-out (TOWO) logic, i.e. the relay operates when the locus exits the inner zone, such misoperation can be avoided. However, the TOWO logic is proved to be insufficient to recover transient stability in some cases during the design stage.

In Fig. 8, the relay fails to operate during an unstable swing because the swing locus swerves around the inner zone. This is unexpected in the design stage and is caused by increased penetration of renewable generation.

In addition to unexpected swing trajectories, decreased dwelling time within inner and outer zones of relay characteristics is another issue caused by renewable penetration. It can be seen from the relay settings shown in Table 2 that the OST time delay decreases dramatically when PPL increases. Unstable swings may be mistaken for short-circuit faults when the scheme is used in systems with higher APLs.

4.2 Results on GB 29-zone system

The GB 29-zone system provides four grid models with different renewable penetration levels. With a displacement of SGs by WGs in multiple zones, the system may respond differently to the same disturbance. A number of separation patterns can be identified for each horizon year depending on the disturbance experienced.

Table 4 tabulates the separation plan determined using the systematic approach mentioned previously, including relay locations, created islands and separation boundaries for each pattern. It can be concluded that coherent generator groups change dramatically between years. With increasing renewable penetration, fewer separation patterns can be observed. Relays need relocation when penetration level changes, otherwise unnecessary or missing separation may happen.

OST relays in this system are set the same way as in the modified two-area system. TOWO is used in scheme design because using TOWI cannot distinguish some stable swings from unstable ones. Two relays are used for each pattern to improve security by allowing operation only when both relays detect out-of-step. The designed OST schemes are tested in both the original system and system with 50% of original penetration level. This is to investigate the performance of the scheme considering variable penetration level as seen in practice. An example of how OST protection protects transient stability is presented below.

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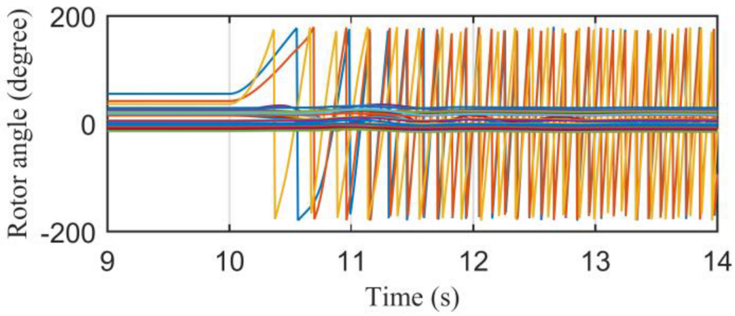

Fig. 9 *Transient instability without implementing OST*

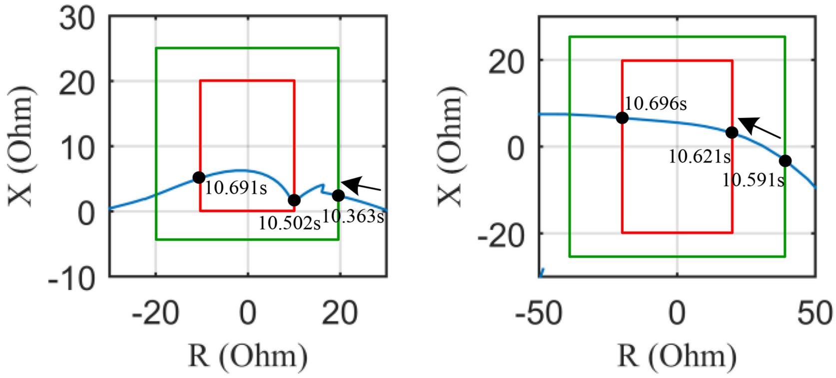

Fig. 10 *Impedance loci measured by relay 2-4 (left) and relay 3-4 (right)*

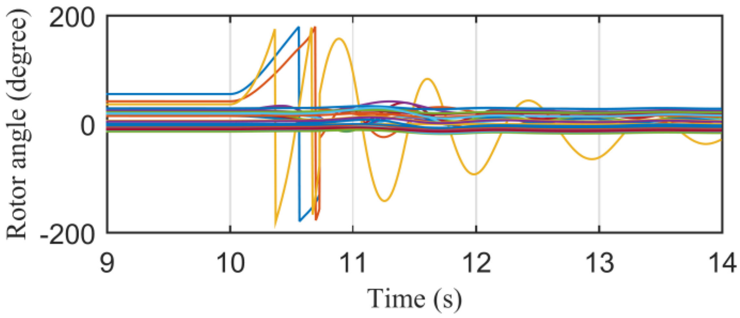

Fig. 11 *Transient stability recovered after separation*

Table 5 Relay performance in GB 29-zone system

Year	APL, %	No. of unwanted separations	No. of missing separations	Success rate, %
present	17	0	6	99
	8	0	57	82
2020	34	0	0	100
	17	0	33	83
2025	63	0	0	100
	32	0	30	90
2030	78	0	0	100
	39	0	357	47

Fig. 9 shows the change in generator rotor angles when the system experiences an unstable swing. The swing is induced by a three-phase fault occurring at the receiving-end of Lines 1–3 and cleared by opening that line 400 ms after fault inception. In this case, generators 1–3 lose synchronism with the rest of the system. According to the proposed separation plan, Relays 2-4 and 3-4 should be responsible for separating zones 1–3 from the system. Impedance loci measured by both relays are shown in Fig. 10. Out-of-step is declared by relays 2-4 and 3-4 at 10.691 and 10.696 s, respectively. System separation is initiated at 10.696 s, separating zones 1–3 from the system. Transient stability is recovered, which can be seen in Fig. 11.

Simulation results regarding success rate and the number of unsuccessful operations of the proposed OST scheme are tabulated in Table 5. It can be concluded that the proposed scheme can achieve a minimum of 99% success rate when the renewable penetration level is equal to what presumed, i.e. APL = PPL. It is worth noting that under no circumstances the scheme separates the system unwantedly. This is due to the fact that the TOWO logic is used, which is more secure than TOWI logic. However, missing separation becomes very common when the system is operated with a halved penetration level. This reduces the success rate of the scheme dramatically. To sum up, the investigated OST scheme can only perform ideally in the system for which it is designed. This is in line with the conclusion made from results on the modified two-area test system.

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5 Conclusion

This paper investigates the impacts of renewable integration in power systems on the operation of the conventional impedance-based OST scheme. A systematic approach is used to set OST relays in a modified two-area system and a GB 29-zone system under different renewable penetration levels. An extensive number of simulations are carried out to test the designed OST scheme under various penetration levels. It is deduced that OST protection performs acceptably only in the system for which the scheme is designed for. Variation of penetration level can lead to altered coherent generator groups, swing frequency and impedance trajectories. The performance of impedance-based OST scheme is compromised because settings of the scheme cannot reflect changes in system condition in real time. Unnecessary creation of islands and loss of system stability are among the possible consequences of this shortcoming of OST scheme design. It follows that the conventional impedance-based OST scheme needs timely adjustment before they can be applied in a system with increasing renewable penetration. Otherwise, the development of new approaches to achieve OST protection that are immune to the impacts of network reconfiguration is urgently needed.

6 Acknowledgments

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