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RESEARCH ARTICLE

Protection Enhancement in Modern Distribution Networks Considering On-Load Tap Changer Operations Side-Effects

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ABSTRACT This paper shows that since high penetration level of distributed generations (DGs) makes the protection coordination complicated in active electrical grids, selectivity task among relays pairs can be easily affected by on-load tap changer (OLTC) tap position. Therefore, mitigating the side effect of OLTC tap position on relays coordination in active distribution networks is of crucial importance which should be considered in relaying process. To tackle this challenging issue, this paper presents a protection scheme based on deployment of numerical relays and low bandwidth communication links besides considering OLTC tap position. The proposed approach provides a selective scheme with individual settings for relays which are set independent from OLTC tap positions. The relays settings are obtained through the optimization process to minimize the relays tripping times. In this regard, a new logarithmic objective function (OF) is also presented to steer the relays setting toward optimal solutions with fast convergence. The feasibility and the effectiveness of the proposed formulation is tested on the IEEE 14-bus test system.

INDEX TERMS Distributed generations (DGs), modern distribution networks on-load tap changer (OLTC), protection scheme.

I. INTRODUCTION

The introduction of modern distribution networks, characterized by active features, aims to improve performance, reliability, and economic indices. Despite these advancements, the complexity of the overcurrent protection process has increased owing to technical challenges such as bidirectional power flow and new selectivity constraints in these networks. Furthermore, the growing penetration level of distributed generations (DGs) necessitates on-load tap changer (OLTC) operations for voltage control, adding an additional layer of complexity to the protection task. The evolving protection landscape in modern distribution networks underscores the requirement for innovative protective devices and models [1].

Various studies in the literature have addressed the challenges of overcurrent relaying in distribution networks characterized by interconnected and active features. These efforts can be broadly categorized into two main trends. The first line of research focuses on leveraging different optimization methods to determine optimal relay settings, aiming to minimize miscoordination and relay operation time. In this manner, directional overcurrent relaying is implemented using both trial-and-error and deterministic approaches in [2] and [3]. However, these methods often face with computational challenges owing to increasing complexity [4]. Linear programming techniques are also explored in [5] and [6], but issues arise when dealing with nonconvex and nonlinear configurations, where the initial guess may prove inefficient [7], [8].

In response to the advancements in processors, heuristic algorithms have emerged as potent optimization tools, as demonstrated in [9], and have found practical applications

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in [10] and [11] for similar mission. Moreover, a comparative study among various meta-heuristic optimization methods is presented in [12]. Hybrid methods are also tested in [8], [13], and [14], with [15] comparing an interior point algorithm with different hybrid algorithms. Some methods introduced new penalty functions [15], [16], [17], [18], resulting in faster and more selective protection. However, the improvement in protection quality is noted to be modest, and achieving the selectivity requirements of real modern distribution networks remains challenging. Furthermore, in [19], it is demonstrated that the selectivity task among relay pairs can be influenced by OLTC tap position. Meeting the associated constraints is found to increase the tripping time of directional overcurrent relays (DOCRs) which in turn emphasizing the intricate interplay between OLTC operations and selectivity of the protection.

The second research line alludes to the deployment of digital relays, leading to the development of relays coordination to maintain selectivity tasks while providing rapid-response protection. In this regard, methods outlined in [20], [21], and [22] aim to present effective inverse characteristics for relays through optimization processes. In order to protect radial distribution networks, new piecewise characteristics for overcurrent relays are introduced in [23]. Including an auxiliary variable into the relay operation time model results in a new inverse characteristic in [15], thereby paving the way of selectivity constraints fulfillment in modern distribution networks. Furthermore, based on new and numerical relays, communication-assisted schemes are presented in [24] and [25]. In [26], new layer is also employed in conjunction with the conventional characteristics, satisfying relaying tasks through the use of communication links. This approach is also further extended based on a user-defined coordination strategy in [27]. While these schemes enhance flexibility in relaying and improve the obtained solutions, it is noteworthy that the earlier mentioned challenges associated with changes in OLTC tap positions are overlooked in these studies.

This paper endeavors to formulate a new protection scheme aimed at addressing the challenges posed by OLTC tap position changes in the coordination of relays within modern distribution networks. The proposed protection scheme is predicated on the integration of numerical relays and low-bandwidth communication links. Within this framework, numerical relays are endowed with an additional attribute designed to protect the reverse direction, thereby functioning as a new backup protection for conventional primary relays. In this process, to prevent the mal-operation of conventional backups, the employed communication links facilitate the transmission of blocking signals from primary relays, effectively blocking these conventional characteristics. This innovative scheme not only enhances flexibility in the coordination process but also effectively can address the constraints associated with OLTC tap positions. Moreover, this paper introduces a new OF tailored to guide relay settings towards optimal solutions with swift convergence. To validate the feasibility and effectiveness of the proposed approach, extensive testing is conducted on the IEEE 14-bus test system. In summary, contributions of this study are outlined below:

- A new protection scheme is presented to tackle challenges arising from OLTC tap position changes in relay coordination;
- The proposed protection scheme is based on the integration of numerical relays and low-bandwidth communication links, presenting a comprehensive approach to enhance the reliability of relay coordination;
- The new approach is also introduced by incorporating a new dynamic OF into optimization process. The dynamic OF plays a pivotal role in determining the optimal solution within the spectrum of feasible alternatives.
- Relays characteristics are also optimized for presenting fast-response protection.

As known, overcurrent coordination with single fault point may jeopardize selectivity tasks along the protected lines. In this paper, as well as near-end faults, coordination time interval (CTI) are also satisfied in far-end fault to prevent this issue. In this paper, section II deals with OLTC tap position issue on relaying. Also, the proposed protection approach for meeting this problem is tailored in modern active distribution networks. Section III follows the problem formulation based on the proposed scheme and new objective function (OF). Section IV addresses the test system specifications and articulates about the simulation setups. The obtained results are pointed out in Section IV. Eventually, Section V concludes the manuscript.

II. PROPOSED METHOD

Here, first, OLTC side effects on protection coordination of DOCRs are illustrated to show the essence of meeting the constraints associated with OLTC tap positions in coordination process. Afterward, the devised protection scheme based on deployment of numerical relays and communication links is elaborated and presented. Finally, in this study, the new approach is also introduced by incorporating a new dynamic OF into the control framework of optimization. The dynamic OF serves as a mathematical expression that is subject to minimization, playing a pivotal role in determining the optimal solution within the spectrum of feasible alternatives. Unlike static OFs, the dynamic nature of this formulation allows for real-time adaptation, enabling the optimization process to continuously reassess and optimize its performance based on evolving conditions.

A. SIMULATION-BASED ANALYSIS: OLTC TAP POSITION IMPACTS ON PROTECTION COORDINATION

At the outset, the process of selecting taps in an on-load transformer tap changer system without causing power supply interruption or short-circuiting winding turns is described. Fig. 1 shows a simple test system with an on-load transformer tap changer. The demonstration in Fig. 1 begins with the tap changer at position 2, supplying load through the upper-side connection with diverter resistor A short-circuited. Moving to tap 3 triggers a sequence where switch 3 closes, directing load

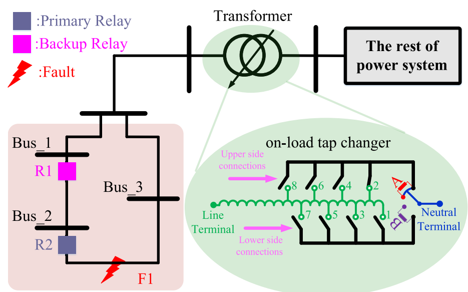

FIGURE 1. Simple testbed: Selecting taps by on-load transformer tap changer.

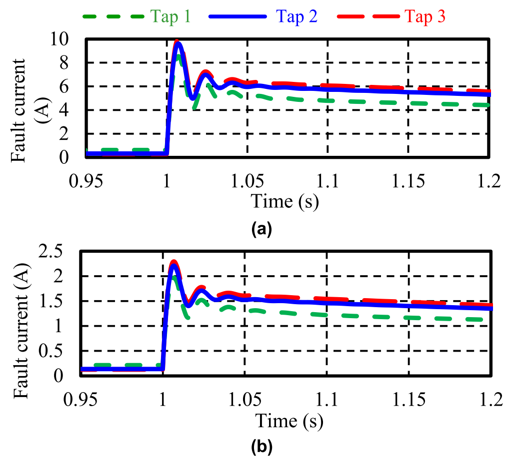

FIGURE 2. Fault currents of a): primary and b): backup relays for a fault at F1 with different tap position.

TABLE 1. Selectivity satisfaction of relay pairs in different OLTC taps.

Pair's No.	CTI satisfaction		Pair's No.	CTI satisfaction	
	Tap-1	Tap-2		Tap-1	Tap-2
1	✓	✓	13	✓	×
2	✓	✓	14	✓	×
3	✓	✓	15	✓	×
4	✓	×	16	✓	×
5	✓	×	17	✓	×
6	✓	×	18	✓	×
7	✓	×	19	✓	×
8	✓	×	20	✓	×
9	✓	×	21	✓	×
10	✓	×	22	✓	×
11	✓	×	23	✓	×
12	✓	✓	24	✓	×

through diverter A, then through both A and B, and finally solely through diverter B. The rotary switch further turns, shorting diverter B, redirecting the load to the lower-side connection, while diverter A remains unused. Finally, switch 2 opens in an off-load operation, completing the tap-changing process.

Here, a series of simulations are performed to illustrate that OLTC tap position can affect the protection coordination of DOCRs. First, fault currents of a primary relay and a backup one for a fault at F1 are presented in Fig. 2 with different tap position. As can be seen, by changing tap position, the current seen by relays are changed which may cause miscoordination.

To demonstrate the issue of miscoordination, the coordination of relays follows the approach outlined in [10]. During this coordination process, relays are coordinated with the fault currents identified in the primary configuration of the IEEE 14-bus test system. Table 1 provides a summary of the discrimination times obtained for the relays in two different cases. This table serves to indicate whether the selectivity requirements between pairs of relays, situated in two distinct tap positions, have been successfully fulfilled. As depicted, in the first tap position, all relays effectively meet the selectivity tasks, showcasing a coordinated response. However, in the next case, when the tap position is altered, certain pairs of relays fail to satisfy selectivity tasks, leading to recorded of miscoordination. Consequently, in systems incorporating overcurrent protection, there is a critical need to devise a new protective system that addresses and resolves this significant problem.

B. PROPOSED METHOD BASED ON DUAL-SETTING RELAYS AND COMMUNICATION LINKS

For reliable protection in modern active distribution networks, it is essential to satisfy not only the conventional selectivity constraints but also the constraints associated with OLTC stage settings. To do so, the recently developed dual-setting DOCRs are used for devising new protection scheme to tackle this challenging protection problem. Dual setting relays are capable to protect two different directions with individual settings and characteristics that are numerically determined without using another relay. That is, this relay can play a role of two individual DOCRs for protecting two different feeders which are connected to the same bus. Based on utilizing these kind of relays, new backups can be taken into consideration for relays with primary tasks. In the proposed scheme, the first characteristic is employed for protecting forward direction and the second characteristic is used for protecting reverse direction. Fig. 3 elaborates the basic concept of proposed scheme in comparison with the conventional approach. In this regard, Fig. 3 (a) shows the conventional relaying scheme and Fig. 3 (b) is for exploring the proposed approach based on dual setting relays. As can be seen, in the conventional scheme, for a fault at Line1, the relay R1 is responsible for generating tripping signal and R3 plays the backup role for R1. Therefore, in the case of failure of R1, R3 would clear the fault after a specified time which calls CTI. This is while; by using the proposed scheme based on using dual setting relays, R1 is the primary relays for clearing fault and the backup task is with reverse curve of R2. In this scheme, to prevent maloperation of R3 for faults at Line1, R1 also sends a blocking signal to R3 through the low bandwidth communication links such as tele-protection. Therefore, in the coordination process, suitable selectivity tasks should be contemplated among R1 and reverse characteristic of R2 to guarantee reliability. Furthermore, telecommunications are only considered for blocking the conventional backup relays and they do not have any effect on tripping of primary relays. Hence, in the case of

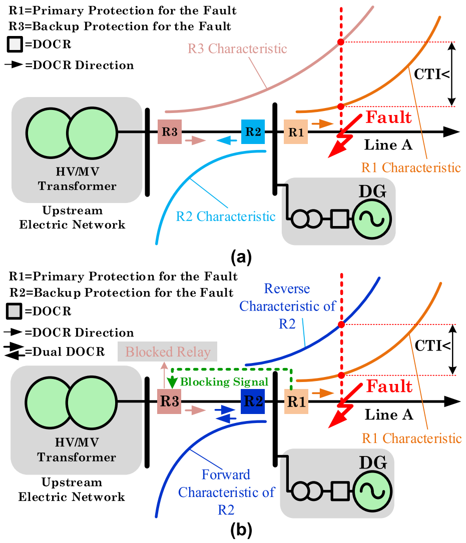

FIGURE 3. **Protection scheme based on using (a): conventional scheme and (b): proposed scheme.**

unexpected delays or malfunctions of communication links, faults would be cleared in a timely manner by primary relays. For example, for the injected fault in the Line1 in Fig. 3 (b), R1 trips to clear the fault with of effect tele-protection. When, R1 fails to clear the fault and owing to malfunction or failure in communication link, R2 might not be able to have a proper response. In this case, the forward direction of R3 can clear the fault, successfully. Hence, fault clearance would not be imperiled.

The inverse characteristic of a DOCR is governed by:

$$t = TDS(\frac{A}{(M)^B - 1}) \tag{1}$$

$$M = {}^{I_{Fault}}\!/_{I_p} \tag{2}$$

Typically, in this characteristic, TDS and Ip are considered as the optimization variables which are adjusted optimally based on different optimization machines. Moreover, the other coefficients of A and B are taken into consideration to be constant [22]. The parameter A is the constant value of relay time inverse characteristics and B indicates the inverse time type. In (2), the fault current which is seen by the DOCR is indicated by I_{Fault}. Meanwhile, in the proposed scheme based on dual-setting DOCRs, there are four optimization variables which needs to be set by optimization algorithms. Two of them are considered for presenting optimal characteristic for protecting forward direction namely TDS_{fw},, Ip_{fw}, and the others are for protecting reverse direction namely TDS_{rv} and Ip_{rv}. On the other hand, numerical relays are able to present more controllable variables. By deployment of dual-setting relays as numerical ones, number of controllable variables can be increased. Thus, in addition to the previous four introduced parameters A_{fw}, A_{rv}, B_{fw}, and B_{rv} can be contemplated as the optimization variables. This approach helps to minimize the effect of OLTC tap position on relays selectivity tasks by providing more flexibility in coordination process.

C. IMPROVING THE EVALUATION STEP IN OPTIMIZATION PROCESS: A NEW OF

To transform a constrained optimization problem into an unconstrained one, various penalties are usually used in the OFs of the optimization problem to steer the corresponding variables toward the optimal solutions. In the literature, various OFs are developed for this task. These OFs contain different parameters set by the users to control the penalty weights for the violated constraints. This is while; in this study, new penalties are used to present a new OF with suitable dynamic properties. In this study, there are two sets of constraints for performing selectivity tasks in the main topology with and without OLTC changes. The following model for OF is recommended to tackle this problem:

$$\min : z = f(x) \tag{3}$$

$$\text{Subject to: } \begin{cases} m_j(x) \leq 0; & for\ j = 1, \ldots, Q \\ e_j(x) \leq 0; & for\ j = Q+1, \ldots, J \end{cases} \tag{4}$$

In (4), m and e are the corresponding constraints to the explained cases. The search space and feasible space are defined by the followings which are denoted by SS and FS.

$$SS = \{x = (x_1, x_2, \ldots, x_n)^T \in R^n : \\ l_n \leq x_n \leq m_n,\ j = 1, \ldots, n\} \tag{5}$$

$$FS = \{x \in R^n \,|\, m_j(x) \leq 0,\ j = 1, \ldots, Q, \\ e_j(x) \leq 0,\ j = Q+1, \ldots, J\} \tag{6}$$

Based on the devised penalties, OF can represented by:

$$\text{OF} = f(x) + \text{pen}_1 + \text{pen}_2 \tag{7}$$

$$\text{pen}_1 = \left[\left[\mu \sum_{j=1}^{Q} (\delta_j \omega_j \Phi(d_j(SS))) + \chi\right] \delta_{SS}\right] \\ \times [ICF_1(it))] \tag{8}$$

$$\text{pen}_2 = \left[\left[\mu \sum_{j=Q+1}^{J} (\delta_j \omega_j \Phi(d_j(SS))) + \chi\right] \delta_{SS}\right] \\ \times [ICF_1(it)] \tag{9}$$

where, ω_j is the weight factor for constraint j, μ is severity factor, $d_j(S)$ is the measure of the degree of violation of constraint j introduced by solution SS, Φ is the function of this measure, χ is the penalty threshold factor, it is the iteration counter, and $ICF(it)$ denotes an increasing function of the current iteration it in the range of (0,..,1). Here, $ICF(it)$ is defined as follows:

$$ICF_1(it) = \left({}^{it}\!/_{Max - it}\right)^{\gamma_1} \tag{10}$$

$$ICF_2(it) = \left({}^{it}\!/_{Max - it}\right)^{\gamma_2} \tag{11}$$

In these equations, γ_1, and γ_2 are constant, Max-it shows the number of iterations, and also:

$$\delta_j = \begin{cases} 1 & \text{if constraint } j \text{ is violated} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

$$\delta_{ss} = \begin{cases} 1 & \text{if } SS \text{ is feasible} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

In this OF, the value of each penalty is shown by Φ. In the conventional OFs, there is a static term that determines the penalties based on a quadratic function for violations in discrimination time of relays [17]. In these approaches, some violations with small value stand as a severe obstacle in obtaining reliable coordination based on quadratic function [18]. On the other hand, increasing the coefficients in the OFs including quadratic function affect the convergence of the optimization algorithm. To meet this problem, another penalty function is devised in [18] based on including a constant penalty for different violations. Thus, the same gravity is considered for all miscoordinations. Thus, presenting a suitable Φ in the devised dynamic OF with capability of passing small violations and creating an appropriate pressure on small and large violations could be of interest. In this study, based on the conducted study in [18] and [28], Φ is considered to be a shifted logarithmic function. Therefore, different pressures on different violations would be provided by the devised OF. Furthermore, the proposed OF does not put unusual pressure on the large violations. Due to presence of two different coordination cases in the coordination scheme, different shifts are contemplated for m and e. As well, the proposed OF has a dynamic feature. The penalty with high degree imposes more pressure to obtain feasible solutions. By doing so, the algorithm moves faster toward solutions with lower violations, even if far from optimal. The penalty with lower degree makes less pressure on feasibility and the optimization algorithm may trap in infeasible solutions [18]. However, the devised OF starts with low pressure and ends in high pressure. It should be emphasized that two groups of constraints are considered to fulfill the selectivity task between relay pairs. In the first group, selectivity tasks are assumed to be satisfied between the relay pairs connected to the main topology. In the second group, selectivity tasks between the relay pairs are satisfied when the OLTC tap position changes the short-circuit capacity. In this method, *m* and *e* are the corresponding constraints to the explained cases, respectively.

III. PROBLEM FORMULATION BASED ON THE PROPOSED PROTECTION SCHEME AND NEW OF

In this section, the proposed protection coordination scheme is formulated which can tackle by optimization algorithms for obtaining relays settings optimally. In this optimization problem, the objective is to minimize the overall operation time of relays while satisfying selectivity constraints. In this study, the OF is considered as follows:

$$F^{operating-time}: \ \min \ T = \sum_{f\in F}(\sum_{i\in I}(t_{i,fw,f} + \sum_{ba\in Ba} t_{ba,rv,f}) \tag{14}$$

here, fw, rv, f, i, and ba indicate forward direction, reverse direction, the points of faults, all dual setting DOCRs, and backup DOCRs, respectively. Likewise, F, I, and Ba are the sets of the fault points, all dual setting DOCRs, and backup DOCRs. Moreover, $t_{i,fw,f}$ is the tripping time of relay i for fault at point f based on forward direction characteristic. Likewise, $t_{ba,rv,f}$ is the tripping time of backup relay b for fault at point f based on reverse direction characteristic. By considering f in the OF, optimization machine can minimize the tripping time of dual setting DOCRs in different fault locations.

A reliable and fast protection for faults isolation renders the need for satisfying a set of constraints. As pointed before, relays in the proposed approach based on the communication-assisted dual setting DOCRs have two characteristics in both forward and reverse directions. The forward and reverse characteristics are presented as follows:

$$t_{i,fw,f} = TDS_{i,fw}\left(\frac{A_{i,fw}}{(^{IF_f}/_{Ip_{i,fw}})^{B_{i,fw}} - 1}\right) \tag{15}$$

$$t_{i,rv,f} = TDS_{i,rv}\left(\frac{A_{i,rv}}{(^{IF_f}/_{Ip_{i,rv}})^{B_{i,rv}} - 1}\right) \tag{16}$$

For keeping selectivity as an important technical requirement, discrimination time (Δt) among relays pairs should be more than zero. As previously described, two sets of constraints should be contemplated. The first set is modeled by the following equations which is considered for meeting selectivity among relays pairs in the case where OLTC tap position is not changed:

$$\Delta t_{k,f} = t_{rv,ba,f} - t_{fw,i,f} - CTI \geq 0 \tag{17}$$

$$m_j = -\Delta t_{ba,fa}, \quad j = 1, \ldots, P \tag{18}$$

$$P = Ba \times Fa \tag{19}$$

The second set is modeled by the following equations which is considered for meeting selectivity among relays pairs in the case where OLTC tap position is changed:

$$\Delta t_{k,f} = t_{rv,ba,f} - t_{fw,i,f} - CTI \geq 0 \tag{20}$$

$$e_j = -\Delta t_{b,fa}^{OC/Dis}, \ j = Q+1, \ldots, J \tag{21}$$

$$J = 2 \times P \tag{22}$$

$$\Phi(d(\Delta t_j)) = \begin{cases} if & \Delta t_j > 0 \quad 0 \\ if & \Delta t_j < 0 \quad \Delta t^2 \end{cases} \tag{23}$$

The constraints associated with the variable's limitations should be considered in the proposed formulation. Here, the limitations for *TDS* and *Ip* are expressed by followings.

$$TDS_{\min} \leq TDS_{fw,i} \leq TDS_{\max} \tag{24}$$

$$TDS_{\min} \leq TDS_{rv,b} \leq TDS_{\max} \tag{25}$$

$$Ip_{\min} \leq Ip_{fw,i} \leq Ip_{\max} \tag{26}$$

$$Ip_{\min} \leq Ip_{rv,b} \leq Ip_{\max} \tag{27}$$

In addition to conventional characteristics, numerical relays are able to follow arbitrary characteristics. Therefore, α and β are also included as variables to be optimized in

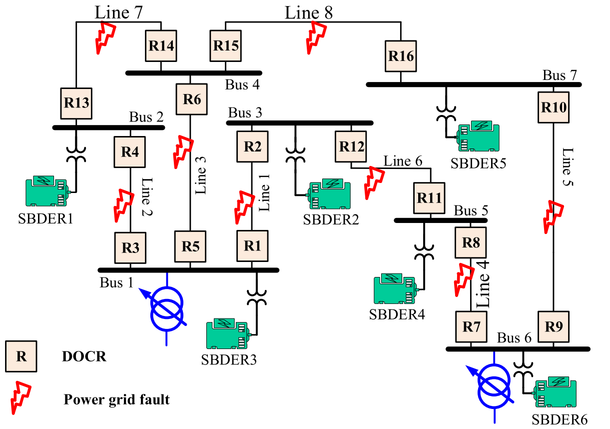

FIGURE 4. The employed test system.

the protection coordination model. Followings are the related constraints.

$$\alpha_{\min} \leq \alpha_{fw,i} \leq \alpha_{\max} \tag{28}$$

$$\alpha_{\min} \leq \alpha_{rv,b} \leq \alpha_{\max} \tag{29}$$

$$\beta_{\min} \leq \beta_{fw,i} \leq \beta_{\max} \tag{30}$$

$$\beta_{\min} \leq \beta_{rv,b} \leq \beta_{\max} \tag{31}$$

Furthermore, the tripping time of each DOCR should be preserved within the minimum and maximum permissible times, represented by (32).

$$t_{\min} \leq t^{OC}_{fw,i} \leq t_{\max} \tag{32}$$

IV. NUMERICAL ANALYSIS AND GENERAL DISCUSSIONS

A comprehensive and extensive numerical study has been conducted to assess the efficacy of the proposed protective scheme in addressing challenges associated with changes in tap positions of OLTC. The devised scheme is tested by using the IEEE 14-bus testbed, as illustrated in Fig. 4. This testbed incorporates 16 DOCRs and is further equipped with six synchronous-based DGs. The locations and capacities of these DGs are determined in accordance with the analysis presented in [29]. Consequently, DG1 to DG6 are allocated capacities of 5, 12, 4, 1, 1, and 5 MVA, respectively, as detailed in [27]. The lower and upper limits of variables are the same with conducted study in [29].

To evaluate performance of the proposed approach, two cases are contemplated. In the first case, the conventional DOCRs are coordinated using the conventional coordination strategy without considering OLTC tap change position. Then, in the second case, the proposed protection scheme is tested where dual setting relays are coordinated with user-defined coordination strategy.

A. CONVENTIONAL APPROACH: FIRST CASE

In this case, the effectiveness of the conventional coordination approach, utilizing conventional DOCRs without the deployment of communication links, is examined. The objective is to determine whether this conventional method can ensure selectivity during OLTC tap position changes. In this approach, an optimization process is undertaken to determine the values of optimization variables such as dial settings TDSs and pickup currents Ips for relays. Furthermore, other parameters in the relays' tripping time function are held constant, determined based on standard inverse characteristics. The coordination of relays is tested for both near-end and far-end fault points. Upon the execution of the optimization algorithm, the resulting settings associated with relays are reported in Table 2. It is observed that the obtained solutions adhere to the specified constraints. As an example, TDSs falling within the range of greater than 0.05 and lower than 3.2. This analysis provides insights into the viability of the conventional coordination approach in meeting selectivity requirements amidst OLTC tap position changes. To this end,

TABLE 2. DOCRs settings in the first case.

Optimal setting of DOCRs					
Relay No.	Parameter		Relay No.	Parameter	
	TDS	*Ip (kA)*		*TDS*	*Ip (kA)*
1	0.9964	0.1729	9	0.4375	0.2184
2	0.4331	0.1729	10	0.307	0.2184
3	0.7270	0.1742	11	0.5118	0.0884
4	0.1	0.1545	12	0.5558	0.0884
5	0.4401	0.4069	13	0.5352	0.0377
6	0.4774	0.3443	14	0.2345	0.0377
7	0.6854	0.1456	15	0.467	0.1274
8	0.8259	0.1456	16	0.4197	0.1274

TABLE 3. Tripping time of DOCRs in the first case and in the main topology.

Relays No.		Fault location					
		Near-end			Far-end		
PR	BR	$t_{primary}$	t_{backup}	Δt	$t_{primary}$	t_{backup}	Δt
R1	R4	1.4779	1.6679	0.0000	-	-	-
R1	R6	1.4779	3.3596	1.6817	-	-	-
R2	R11	0.9782	1.1937	0.0155	1.2570	1.4570	0.0000
R3	R2	1.0570	1.2570	0.0000	1.5485	2.7828	1.0343
R3	R6	1.0570	3.3596	2.1026	-	-	-
R4	R14	0.2300	0.7710	0.3410	1.6779	1.8779	0.0000
R5	R2	0.8005	0.2570	0.2554	1.0828	2.6276	1.3448
R5	R4	0.8005	1.6779	0.6774	-	-	-
R6	R13	1.1248	1.6990	0.0742	-	-	-
R6	R16	1.4248	2.9884	1.3536	3.3596	3.5596	0.0000
R7	R10	1.0894	1.2894	0.0000	1.2134	1.9038	0.4904
R8	R12	1.8458	2.0587	0.0129	2.0096	2.2096	0.0000
R9	R8	1.8096	2.0096	0.0000	2.4986	4.8320	2.1334
R10	R15	1.9712	1.1991	0.0278	1.2894	1.4894	0.0000
R11	R7	1.1340	1.2134	0.0000	1.1937	1.4541	0.0603
R12	R1	1.7689	1.9689	0.0000	2.0587	2.3597	0.1009
R13	R3	1.3485	1.5485	0.0000	1.6990	2.1999	0.3010
R14	R5	0.6182	1.0828	0.2647	0.7710	1.7726	0.8016
R14	R16	0.6182	2.9884	0.1702	0.7710	4.2235	3.2525
R15	R5	0.8828	1.0828	0.0000	1.1991	1.7304	0.2313
R15	R13	0.8828	1.6990	0.6161	1.1991	2.3788	0.9797
R16	R9	2.2986	2.4986	0.0129	2.9884	3.3700	0.1825

TABLE 4. Tripping time of DOCRs in the first case when there is a OLTC tap change.

Relays No.		Fault location					
		Near-end			Far-end		
PR	BR	$t_{primary}$	t_{backup}	Δt	$t_{primary}$	t_{backup}	Δt
R1	R4	1.4683	1.6441	-0.1242	-	-	-
R1	R6	1.4683	3.3337	1.5654	-	-	-
R2	R11	0.9777	1.1932	-0.0845	1.2528	1.4531	-0.0997
R3	R2	1.0507	1.2528	-0.0979	1.5431	2.8677	1.0246
R3	R6	1.0507	3.3337	1.983	-	-	-
R4	R14	0.2293	0.7694	0.2401	1.6441	1.8692	-0.0749
R5	R2	0.7945	1.2528	0.1583	1.0768	2.6855	1.3087
R5	R4	0.7945	1.6441	0.5496	-	-	-
R6	R13	1.4188	1.6920	-0.0268	-	-	-
R6	R16	1.4188	2.9845	1.2657	3.3337	3.5471	-0.0866
R7	R10	1.0884	1.2766	-0.1118	1.2129	1.8656	0.3527
R8	R12	1.8367	2.0499	-0.0868	1.9959	2.1965	-0.0994
R9	R8	1.8072	1.9959	-0.1113	2.4982	4.6363	1.8381
R10	R15	0.9684	1.1951	-0.0733	1.2766	1.4778	-0.0988
R11	R7	1.0130	1.2129	-0.1001	1.1932	1.4513	-0.0419
R12	R1	1.7626	1.9605	-0.1021	2.0499	2.3471	-0.0028
R13	R3	1.3453	1.5431	-0.1022	1.6920	2.1847	0.1927
R14	R5	0.6167	1.0768	0.1601	0.7694	1.7687	0.6993
R14	R16	0.6167	2.9845	2.0678	0.7694	4.2346	3.1652
R15	R5	0.8795	1.0768	-0.1027	1.1951	1.7206	0.2255
R15	R13	0.8795	1.6920	0.5125	1.1951	2.3695	0.8744
R16	R9	2.2983	2.4982	-0.1001	2.9845	3.3648	0.0803

TABLE 5. DOCRs setting in the first case.

Relay No.	Optimal setting of DOCRs							
	Parameter							
	TDS_{fw}	TDS_{rv}	Ip_{fw}	Ip_{rv}	α_{fw}	β_{fw}	α_{rv}	β_{rv}
1	0.1	0.1457	0.1397	0.1397	3.02	1	3.02	1
2	0.1	0.1913	0.1397	0.1397	0.15	0.02	0.15	0.02
3	0.1	0.1	0.1407	0.1407	2.98	1	2.98	1
4	0.1	0.1682	0.1407	0.1407	0.14	0.2	0.14	0.2
5	0.1	0.1	0.3287	0.3287	1.31	0.9	1.31	0.9
6	0.1	0.1543	0.3287	0.3287	0.17	0.11	0.17	0.11
7	0.1	0.1593	0.1176	0.1176	0.17	0.02	0.17	0.02
8	0.1	0.2103	0.1176	0.1176	0.14	0.03	0.14	0.03
9	0.1	0.1098	0.1764	0.1764	0.14	0.02	0.14	0.02
10	0.1	0.1767	0.1764	0.1764	0.14	0.02	0.14	0.02
11	0.1	0.2271	0.0714	0.0714	0.19	0.02	0.19	0.02
12	0.1	0.2388	0.0714	0.0714	0.14	0.02	0.14	0.02
13	0.1	0.2701	0.0305	0.0435	0.26	0.02	0.26	0.02
14	0.1	0.2889	0.0305	0.0305	0.14	0.02	0.14	0.02
15	0.1	0.298	0.1029	0.1029	0.56	0.02	0.56	0.02
16	0.1	0.2181	0.1029	0.1029	0.14	0.02	0.14	0.02

the obtained tripping times for relays based on the reported settings in Table 2 are listed in Table 3. In this case, relays pairs can satisfy selectivity tasks and there is not any record of miscoordinations. For sake of testing the protection performance in the case of OLTC tap changes, tripping times of relays at different tap position is reflected in Table 4. As can be seen, there are some records of miscoordinations which imperil the selectivity tasks in the protection system. Hence, presenting a new protection scheme in meeting this challenging issue seems to be of importance for improving reliability.

TABLE 6. Tripping time of DOCRs in the second case and in the main topology.

Relays No.		Fault location					
		Near-end			Far-end		
PR	BR	$t_{primary}$	t_{backup}	Δt	$t_{primary}$	t_{backup}	Δt
R1	R13rv*	0.05	0.35	0	0.21	-	-
R1	R5rv	0.05	0.35	0	0.28	-	-
R2	R12rv	0.05	0.35	0	0.21	0.51	0
R3	R1rv	0.05	0.35	0	0.22	0.53	0.01
R3	R5rv	0.05	0.35	0	0.15	-	-
R4	R13rv	0.05	0.35	0	0.15	0.45	0
R5	R1rv	0.05	0.35	0	0.21	0.51	0
R5	R3rv	0.05	0.35	0	0.15	-	-
R6	R14rv	0.05	0.35	0	0.15	-	-
R6	R15rv	0.05	0.35	0	0.21	0.51	0
R7	R9rv	0.05	0.35	0	0.21	0.51	0
R8	R11rv	0.05	0.35	0	0.21	0.51	0
R9	R7rv	0.05	0.35	0	0.21	0.51	0
R10	R16rv	0.05	0.35	0	0.21	0.51	0
R11	R8rv	0.05	0.35	0	0.21	0.51	0
R12	R2rv	0.05	0.42	0.07	0.21	0.51	0
R13	R4rv	0.05	0.36	0.01	0.21	0.51	0
R14	R6rv	0.05	0.35	0	0.21	0.54	0.03
R14	R15rv	0.05	0.47	0.12	0.21	0.73	0.22
R15	R6rv	0.05	0.35	0	0.21	0.51	0
R15	R14rv	0.05	0.35	0	0.21	0.51	0
R16	R10rv	0.05	0.35	0	0.21	0.51	0

* rv: reverse characteristics

TABLE 7. DOCRs setting in the first case.

Pair's No.	CTI satisfaction		Pair's No.	CTI satisfaction	
	Tap-1	Tap-2		Tap-1	Tap-2
1	✓	✓	13	✓	✓
2	✓	✓	14	✓	✓
3	✓	✓	15	✓	✓
4	✓	✓	16	✓	✓
5	✓	✓	17	✓	✓
6	✓	✓	18	✓	✓
7	✓	✓	19	✓	✓
8	✓	✓	20	✓	✓
9	✓	✓	21	✓	✓
10	✓	✓	22	✓	✓
11	✓	✓	23	✓	✓
12	✓	✓	24	✓	✓

B. PROPOSED PROTECTION APPROACH: SECOND CASE

In this study, the proposed protection coordination approach, which is based on communication-based dual-setting DOCRs along with the introduced dynamic OF, is investigated using the same test system as in the previous case. As mentioned earlier, dual-setting relays are numeric and can adhere to a user-defined coordination strategy. Consequently, the optimization variables in this case encompass *TDS*, *Ip*, as well as α, and β of the forward and reverse characteristics. After the execution of the optimization algorithm, the resulting settings associated with dual-setting DOCRs are documented in Table 5. Furthermore, the corresponding tripping times for relays, based on the reported settings, are presented in

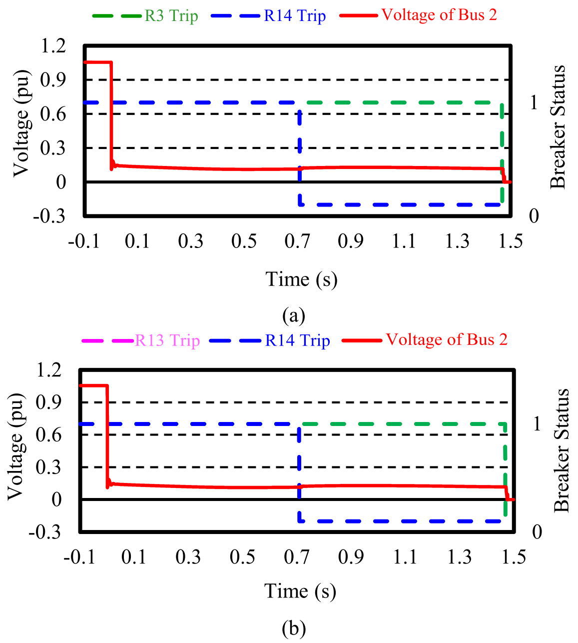

FIGURE 5. Bus 3 voltage recovery based on the protection used in (a): First case and (b): Second case.

Table 6. Notably, in scenarios without OLTC tap changes, the tripping time of relays is observed to decrease. As an illustrative example, in the previous case, Relay R1 cleared the near-end fault at 1.47 seconds. However, in the current case utilizing the proposed protection coordination approach with communication-based dual-setting DOCRs and the introduced OF, the fault is cleared immediately. This notable reduction in clearing time highlights the enhanced performance achieved by the proposed protection scheme in responding swiftly to fault conditions. Moreover, relay pairs demonstrate the ability to fulfill selectivity tasks without any miscoordination. To assess the protection performance in the context of OLTC tap changes, the satisfaction of selectivity tasks under two different tap positions is detailed in Table 7. Importantly, there are no records of miscoordination, and selectivity tasks are consistently and fully satisfied. Consequently, the proposed approach not only reduces the tripping time of relays but also excels in meeting selectivity requirements, underscoring its superiority in protection of modern distribution networks.

Moreover, Fig. 5 illustrate the performance of the conventional and proposed scheme in RMS simulation environment of PowerFactory software. In this simulation study, a three-phase fault with 0.5-ohm resistance is injected at 20% of Line 7 and the voltage of Bus 3 is observed during simulation time for both cases. In these cases, by considering an error with 0.1s magnitude, protection schemes are tested. As can be seen, due to operation of backup relay faster that the primary one, voltage of this bus in the conventional approach reach to zero. This is while; by employing the proposed approach the voltage of bus 3 recovers which show that this error could not imperial the selectivity task of these relays.

V. CONCLUDING REMARKS

This study was undertaken with the aim of addressing the DOCRs coordination challenges in modern distribution networks taking into account the OLTC positions. The initial investigation revealed that the OLTC tap position exerts a notable influence on the short-circuit capacity of the network, thereby altering the magnitudes of fault currents and posing a threat to the selectivity objectives of the protection system. Consequently, this paper introduces a new protection scheme, leveraging numerical DOCRs and employing low bandwidth communication links, as a strategic response to this intricate issue. Moreover, the proposed scheme enhances coordination flexibility appreciably. In this scheme, a new dynamic optimization framework has been also devised to find the relay settings by steering them towards an optimal solution. The form of the OF in this framework was critical to give desirable solutions for driving a system to a desirable state or along a desired trajectory. Within the purview of the proposed methodology, the following results have been identified as the main conclusions of the conducted study:

- The proposed approach was able to provide fast-response protection;
- It was seen that, based on new protection scheme, OLTC tap position effect is diminished which improves the reliability of protection system;
- It was shown that the obtained flexibility based on the dynamic OF helps to steer the relays setting toward the optimal solution and relays can meet selectivity tasks during OLTC tap changes.

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