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Abstract— **This paper investigates the coordination problem of overcurrent relays (OCRs) in presence of wind power generation and electrical energy storage (EES) systems. As the injected short-circuit current of inverter-based devices connected to the electrical grid is a function of the power electronic withstand capacity, the short-circuit level would be limited for these types of devices. Furthermore, since the short-circuit current is a function of the pre-fault current, it is highly needed to take different conditions into account to accurately evaluate the injected current by such devices. This would mainly matter for the EES system operating in either charging or discharging modes, as well. This paper evaluates different operation strategies considering the variations of the load demand and the presence of large-scale wind farms as well as an EES system, while validating the suggested method for coordinating the directional OCRs (DOCRs).**

Keywords—Directional Over Current Relays; Energy Storage Devices; Inverter-based Generation Units;Optimal Operation.

I. INTRODUCTION

Power system protection is a key part of the power system to ensure a reliable and secure operation in case of fault events or any normal operations that cause disturbances that may be misinterpreted as faults. In this respect, the speed and the accuracy of the protective relays in detecting the faults and sending the tripping signal to circuit breakers are highly important. Short-circuit current path would be different for different faults in transmission systems due to the existing lines and meshes. The fault current can flow from a line to a bus or circulate in a low-impedance path in a meshed power system. Hence, it is necessary to use directional overcurrent relays (DOCRs) to recognize the fault current direction. In large power systems, as there are many overcurrent relays (OCRs), there should be time coordination for the protective relays to detect and clear the probable faults as fast as possible.

The DOCRs coordination is defined as determining the time dial setting (TDS) and plug setting multiplier (PSM) [1]. In order to avoid any overlap between the primary and backup protection for an occurred fault, a coordination time interval (CTI) should be considered. Numerous papers have been so far published regarding the DOCR coordination [2-7]. The PSM has been determined experimentally with respect to the load demand and fault currents using linear programming (LP)-based techniques [1], while the only variable of the problem is

finding the TDS subject to the constraints of the primary and backup protection coordination; i.e., CTI [6, 8]. However, the relay's sensitivity is improved by choosing the pickup currents close to the minimum values [4]. If PSM is also taken into account, the above-mentioned optimization problem would turn into a mixed-integer non-linear programming (MINLP) problem. The heuristic methods have been proposed in most research works to solve the MINLP problem. In this respect, various optimization methods have been presented to optimally coordinate the DOCRs. As an example, authors in [9] have utilized particle swarm optimization (PSO) capable to handle the miscoordination problem by considering this issue in the objective function, while authors of [10] have taken the impacts of wind power generation into account. Likewise, an optimization framework has been proposed in [11] using teaching-learning based optimization (TLBO). Besides, a modified adaptive TLBO (MATLBO) and firefly algorithm (FA) has been proposed in [12]-[13], respectively.

On the other hand, penetration of renewable energy resources has been increased in the last decade which results in many benefits from social, environmental, and economic aspects. The inverter-based renewable power generation technologies using control techniques with small time response are able not only to control the injected power to the grid during the fault occurrence, but also to stay connected to the grid over a rational time, generally between one-fourth cycle to seven cycles with respect to the type of the inverters [14].Therefore, one of the severe challenges in protecting the power system in presence of the inverter-based generation units would be the contribution of such units in facing the short-circuit current injection to the fault and their contribution to fast and accurate fault detection. In this regard, several methods have been proposed so far to enhance the performance of inverter-based units both theoretically and in practice. For instance, synchronous condensers as utilized in Denmark, flywheels, batteries and ultra-capacitors are of devices which can be employed for fault current compensation in the network [14]. This paper investigates the fault current assessment in the presence of inverter-based units and an ESS to simulate their contribution to the fault current under particular daily operation conditions.

The remainder of this paper is organized as follows: Section II is devoted to the impact of the inverter-based DGs

on the short-circuit current. Section III includes the mathematical modeling of DOCRs' optimal coordination problem for a fixed network topology. Section IV provides some notes regarding the optimal operation of power systems including large-scale wind farms and energy storage devices based on the unit commitment (UC) model. Section V comprises the simulation results and finally some relevant conclusions are drawn in section VI.

II. THE IMPACTS OF INVERTER-BASED UNITS ON SHORT-CIRCUIT CURRENTS

Inverter-based units are used in renewable energy systems like wind turbines (WTs), photovoltaic (PV), parking lots' inverters in vehicle-to-grid (V2G) operating mode and also in battery-based EES systems. These assets may use different AC-DC and DC-AC converters. The first type is used in units with DC power generation while the second type is used in assets with AC power generation such that the voltage and frequency are adapted to the grid. The full-scale power converters of AC-DC and DC-AC types are used for WTs with permanent magnet synchronous generator (PMSG), wound rotor synchronous generator (WRSG), and squirrel cage induction generator (SCIG). On the other hand, partial-scale power converters are used for doubly-fed induction generators (DFIG) wind turbines. However, the AC power output of the mentioned generators is important from the grid-side viewpoint, regardless of the converter type. Inverters do not have any inertia compared to the conventional synchronous generator-based units. Thus, there is no potential to release the stored energy related to the mass inertia during contingent events. In other words, although the control systems of the inverters have fast response and large flexibility when connected to the grid, such features are considered as severe challenges for the power system protection. In inverters based on phase-locked loop (PLL) known as grid following inverters, the reference signal for control system uses the voltage and frequency of the grid. Hence, the main question in power systems with remarkable penetration of such inverters is based on the droop control strategy known as grid forming inverters. In such inverters, a linear model is defined describing the relationship of active and reactive power with voltage and frequency. Thus, it is likely to define virtual synchronous machines or virtual inertia in the control system of the inverter through modeling the inertia response of synchronous machines.
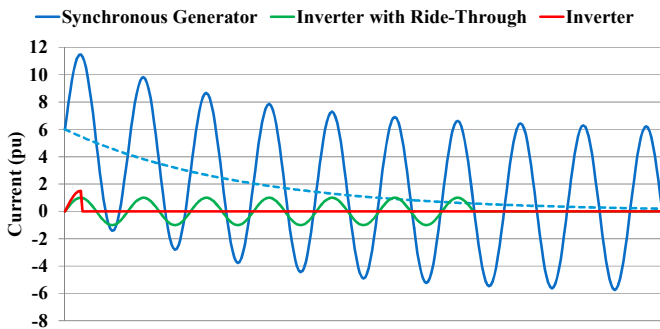

Fig. 1. Fault currents compared to time for a synchronous generator, an inverter with rapid disconnect, and an inverter with ride-through capability [14]

Besides, inverter-based units have fault ride-through capabilities. By appropriately and optimally designing the converter, the wind and storage inverters would be capable of riding through different balanced and unbalanced under-voltage and over-voltage faults.

Moreover, they would be able to tolerate frequency excursions leading to enhancing the electric power system reliability. In case of a fault occurrence, such devices are able to inject reactive current to support post-fault voltage recovery. When a fault occurs, synchronous generator-based units inject current about four to six times greater than the rated value [14]. This current can be utilized as a proof of specific types of faults used in in OCRs to detect the fault. On the contrary, inverter-based units do not have such behaviors. When a fault occurs, inverter-based units detect the fault very fast and avoid any further current injection in 0.25 cycles while they are also able to inject current for a few cycles during a fault. Fig. 1 depicts the short-circuit currents for a synchronous generator, an inverter with rapid disconnect from grid side, and an inverter with ride-through capability.

III. OPTIMAL COORDINATION OF DOCR RELAYS

The problem of DOCRs coordination can be modeled within standard MINLP framework aimed at minimizing the fault clearing time using primary relays, TP_i, in the network.

$$Min \ \sum_{i=1}^{N} TP_i \tag{1}$$

where

$$TP_i = \frac{0.14 \times TDS_i}{\left(\dfrac{I_i^F}{PSM_i \times CTR_i}\right)^{0.02} - 1}, \ i = 1, 2, ..., N \tag{2}$$

Subject to:

$$TB_{j,i} = \frac{0.14 \times TDS_j}{\left(\dfrac{I_i^F}{PSM_j \times CTR_j}\right)^{0.02} - 1}, \ j = 1, 2, ..., N \tag{3}$$

$$TP_i^{Min} \leq TP_i \leq TP_i^{Max} \tag{4}$$

$$TB_j^{Min} \leq TB_{j,i} \leq TB_j^{Max} \tag{5}$$

$$TDS_i^{Min} \leq TDS_i \leq TDS_i^{Max} \tag{6}$$

$$PSM_i^{Min} \leq PSM_i \leq PSM_i^{Max} \tag{7}$$

$$TB_{j,i} - TP_i \leq CTI \tag{8}$$

The clearing time of primary relays, TP, and backup relays, TB, are determined using (2) and (3). In this paper, the Standard Inverse characteristic based on IEC Standard is considered for all overcurrent relays. The current flowing through the primary relay is used to calculate TB in order to determine that with the backup protection setting, i.e. TDS and PSM, how long it takes that the backup relay sends the tripping signal. The clearing time of a relay must be within the permitted range. Moreover, TDS of each relay as a time setting of the relay must be within an acceptable range.

Fig. 2. Optimal operation plan for grid, thermal units and the EES system.

Fig. 3. Forecasted power of wind farms.
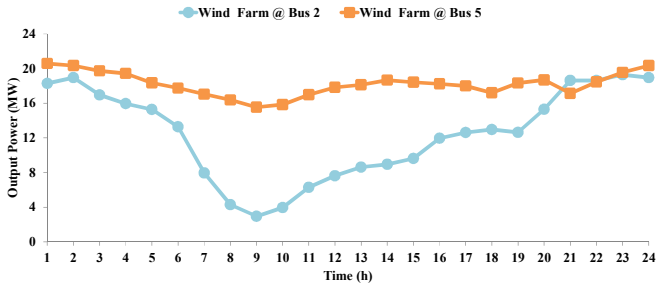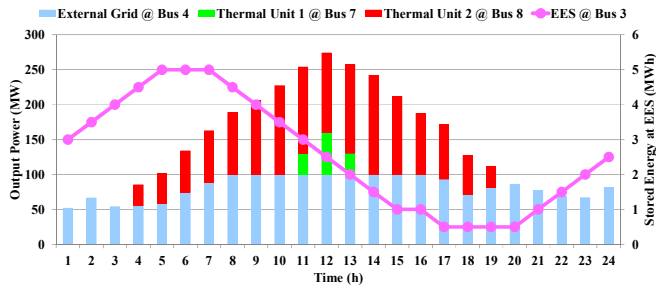
This value can be either continuous or discrete (7). Also, as stated in (8), there should be a *CTI* to avoid any overlap between the operation of primary and backup protective relays. *TDS* is assumed to be in [0.1-1.1] and *CTI* to be 0.3 seconds in this paper. However, seven discrete setting multiples are taken into consideration to draw a comparison as (0.5, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5). Besides, the current transform ratios of the OCRs (1, 2, 4, 5, 6, 8, 10, 11, 12, 13) and (3, 7, 9, 14) are (1200:5) and (800:5), respectively [15].

IV. OPTIMAL DAILY OPERATION OF POWER SYSTEM IN THE PRESENCE OF WIND FARMS AND ENERGY STORAGE DEVICES

The power system operation strategy in presence of fossil-fuel generating units, renewable energies and EES system can be determined so that the total operating costs are minimized, while satisfying the load demand. Heretofore, economic load dispatch (ELD), optimal power flow (OPF), generation scheduling and UC have been developed.

The decision variables of the UC problem are the status of generation units and the power generation levels for committed units. Considering the start-up and shut-down costs of the generating units, the UC problem would determine the best strategy for supplying the hourly loads in an economic way. The fossil-fuel fired units would face different operating conditions due to their fuel consumption and corresponding operating costs in such conditions. It is evident that over the peak hours, the system operator has to dispatch the expensive power generating units in order to supply the demanded power. While, in the off-peak hours, by implementing the UC program, some of these units are shut down due to their high operating costs. It means that in such a case, the generators' circuit breakers would be opened and so, such units could not inject power into the grid. However, the renewable energy resources have different operating conditions. As the operating costs of such units are not considerable, and the injected power

of such units is merely dependent upon the meteorological conditions, it is expected that these units stay on-line during the operational horizon. The system operator could handle the fluctuations of generated power from these units by implementing the energy management system (EMS) in real-time conditions.

Reference [16] has modeled the optimal scheduling of generating units and EES system as a sub-problem of the power system operation in an MINLP framework. In this respect, the optimal dispatch of thermal generating units as well as charging/discharging of the EES system over the 24-hour horizon have been obtained taking the power generated by wind farms into consideration. Assuming that the obtained results are optimal, Fig. 2 shows the energy stored in the EES system in line with the aggregated optimal power generations of external grid and thermal units. Fig. 3 illustrates the forecasted power of wind farms.

V. SIMULATION RESULTS

The proposed framework is implemented on a standard 8-bus test system using data of protective relays, current transformers (CTs), generating units, the external grid as well as the load demand data reported in [17]. Fig. 4 demonstrates the single-line diagram of the test system. Different short-circuit currents have been reported in the literature while in some cases, the external grid has not been modeled and the impact of the pre-fault load currents have not been taken into consideration. Hence, the protection settings have been differently reported. Besides, different values have been proposed for similar short-circuit currents. For instance, Table I represents the short-circuit currents while the pre-fault currents have been neglected and by considering the impact of the external grid with the short-circuit level equal to 400 MVA. These results are similar to those reported in [15] with an acceptable accuracy. The optimal objective value in [18] has been reported as 10.9499 seconds, while [19] reported different optimal objective functions as 8.8423 seconds and 8.5112 seconds using PSO-TVAC-1 and PSO-TVAC-2, respectively. The obtained optimal relay settings are similar to those reported in [15] by considering the same short-circuit currents and the objective function value is 8.427 seconds.

In Table I, the different short-circuit currents are underlined. It is evident that the obtained short-circuit currents are very close to those reported in [15].
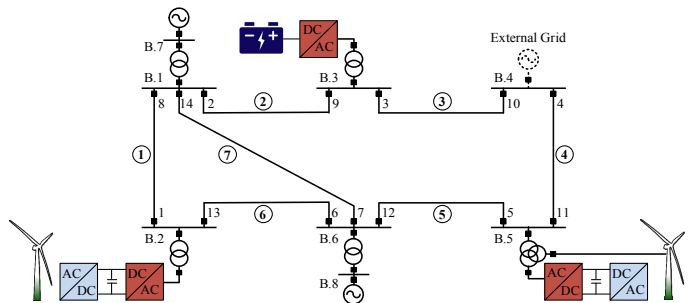

Fig. 4. Single line diagram of 8-bus test system.

TABLE I.   NEAR-END THREE-PHASE SHORT-CIRCUIT RESULTS.

	Reported in [15]		Obtained Results	
(P:B)	Primary	Back up	Primary	Back up
(1:6)	3232	3232	3233	3233
(2:1)	5924	996	5924	996
(2:7)	5924	1890	5924	1889
(3:2)	3556	3556	3556	3556
(4:3)	3783	2244	3782	2243
(5:4)	2401	2401	2401	2401
(6:5)	6109	1197	6109	1198
(6:14)	6109	1874	6109	1873
(7:5)	5223	1197	5223	1198
(7:13)	5223	987	5223	987
(8:7)	6093	1890	6092	1889
(8:9)	6093	1165	6092	1165
(9:10)	2484	2484	2484	2484
(10:11)	3883	2344	3884	2345
(11:12)	3707	3707	3708	3708
(12:13)	5899	987	5899	987
(12:14)	5899	1874	5899	1873
(13:8)	2991	2991	2990	2990
(14:1)	5199	996	5199	996
(14:9)	5199	1165	5199	1165

In this study, hours 9, 12 and 21 have been considered for determining the optimal settings of relays as they are associated with different conditions regarding the committed units, the load demand, the amount of power generation and consequently, different short-circuit levels. Table II indicates the load demand, power generation and the energy stored in the EES system for these scenarios.

The optimal settings of relays for different operation conditions have been addressed in Table III. As can be observed from the results, the increased load demand and the number of committed units lead to the increased clearing time of relays due to selecting larger values for PSM and reducing the effective current seen by relays. Moreover, by decommitting the thermal units, the effective short-circuit current seen by relays decreases, which in turn reduces the PSM of relays, finally enabling the relays to clear the possible faults in a shorter time.

TABLE II.   THE OPTIMAL HOURLY OPERATION OF INSATALLED ASSETS.

Unit	9	12	21
External Grid @ Bus 4 (MW)	100.18	100.31	77.29
Thermal Unit 1 @ Bus 7 (MW)	-*	60.00	-
Thermal Unit 2 @ Bus 8 (MW)	106.01	114.06	-
Wind Farm 1 @ Bus 2 (MW)	2.95	7.62	18.63
Wind Farm 2 @ Bus 5 (MW)	15.54	17.82	17.13
EES @ Bus 3 (MW-MWh)	0.5 (4)**	0.5 (2.5)	-0.5 (1)
Total Active Demand (MW)	225.00	300.00	112.50
Total Reactive Demand (MVAr)	140.625	187.50	70.3125

 * Indicates unit outage
** (*) Indicates stored energy at the end of hour

TABLE III.   THE OPTIMAL SETTINGS OF RELAYS.

Relay	9		12		21	
	TDS	PSM	TDS	PSM	TDS	PSM
1	0.109	2.0	0.100	2.5	0.100	0.6
2	0.150	2.5	0.282	2.5	0.100	0.8
3	0.134	2.5	0.249	2.5	0.100	0.5
4	0.141	2.5	0.194	2.5	0.101	2.5
5	0.111	2.0	0.132	2.5	0.116	1.5
6	0.159	2.5	0.176	2.5	0.122	1.0
7	0.219	2.5	0.268	2.5	0.100	1.5
8	0.105	2.0	0.172	2.5	0.115	1.0
9	0.12	2.5	0.183	2.5	0.116	2.0
10	0.152	2.5	0.212	2.5	0.104	2.5
11	0.127	2.5	0.210	2.5	0.100	0.5
12	0.186	2.5	0.288	2.5	0.100	0.8
13	0.100	0.6	0.100	2.5	0.100	0.6
14	0.104	1.5	0.268	2.5	0.100	1.5
Obj. (Sec.)	7.163		8.960		6.461	

VI. CONCLUSION AND FUTURE WORKS

In this paper, a mixed-integer non-linear programming (MINLP) model was proposed for optimal coordination of DOCRs in presence of inverter-based renewable energy resources and energy storage devices. The optimal coordination problem was tested on a standard 8-bus test system to validate the optimality of the results. Then, for different network topologies achieved from unit commitment problem in a daily operational horizon, the optimal settings were obtained. As a result, for different commitment of installed synchronous generators, different settings have been achieved. Due to diverse power flow through the transmission lines in the meshed grid, it is evident that there would be different short-circuit levels for each generation scheduling. Increasing the number of committed generators at peak hours will increase the short-circuit levels as well as the PSM of relays in the optimal coordination problem. This paper opens a new window for optimal coordination problem under different operation conditions for both meshed and radial topologies and for inverter-dominated smart grids, as well.

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