Joint Optimization of Spatially Coupled Data Center and Fast Charging Station Load Flexibilities in Power System Expansion Planning

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***Abstract*—Data centers (DCs) and fast charging stations (FCSs) exhibit a new type of load flexibility, i.e., spatially coupled load flexibility, which helps prevent congestion in power systems. Compared to the individual optimization, the extra improvement can be achieved with the joint optimization of DC and FCS load flexibilities due to their heterogeneity in spatial scales. However, a demand response approach that considers this cooperation is rarely studied, where one of the main challenges is how to aggregate multiple spatial coupling constraints that with disparate spatial scales. This paper proposes a joint optimization method for spatially coupled DC and FCS load flexibilities to facilitate their full use. First, a physical interpretation for the necessity of the joint optimization is presented. Second, an aggregation model is proposed, which captures heterogeneity in spatial scales, achieves compatibility with varied power system optimization scopes, and emulates a virtual power plant model with multi-port accesses. Third, a coordinated expansion planning model of transmission and distribution systems considering the joint optimization of DC and FCS load regulations, is presented to illustrate the application of the proposed aggregation model. Simulation results verify the efficiency of the proposed aggregation model for the joint optimization.**

***Keywords*—spatially coupled load flexibility, aggregation, data center, fast charging station, electric vehicle.**

I. Introduction

Both data centers (DCs) and fast charging stations (FCSs) have emerged as major electricity consumers. As reported in [1], the estimated global DC electricity consumption in 2022 was 240-340 TWh, which is around 1-1.3% of global final electricity demand. The rapid growth in workloads and 5G wireless technology will bring denser and faster data streams, a trend that is likely to drive up DC demands. In 2021, 0.5 million fast chargers existed. This number is expected to reach nearly 5.5 million and account for almost 550 GW installed capacity by 2030 [2]. As the largest electric vehicle (EV) market, the Chinese government has formulated a plan that proposes adopting fast charging as the main infrastructure and slow charging as a supplement in public charging network [3], a trend that is likely to increase the demand for FCSs.

In particular, in case a workload can be handled in multiple DCs, DCs exhibit a new type of load flexibility: spatially coupled load flexibility, where the load can be transferred among different DCs by dispatching workloads. Specifically, if a workload was intended to be handled in DC m, and this workload is re-dispatched to be handled in DC u, the load in DC m is transferred to DC u. Here, any single DC load reduction can result in an increase in other DC loads, which is the spatially coupled DC load flexibility. Similarly, in case an EV with fast charging demand has multiple FCSs to choose from, FCSs also exhibit spatially coupled load flexibility, where the load can be transferred among different FCSs by guiding the choice of drivers. The significance of spatially coupled DC and FCS load flexibilities has already been demonstrated in some studies: they can help prevent congestion in power systems [4][5]. Their significance will grow progressively in the foreseeable future when DC and FCS power consumption and renewable energy generators represent a more significant portion of power system operations, where issues such as local overload, overvoltage, and undervoltage become increasingly prominent.

Considering that workloads are transferred in a data transmission network and EVs move in a transportation network, data flow distribution laws based on a data transmission network and traffic flow distribution laws based on a transportation network, must be introduced to express spatially coupled DC and FCS load flexibilities in detail, respectively. This makes the scale of variables and constraints significantly increases with the complexity of the data transmission and transportation network structures [6][7]. Therefore, some studies have established aggregation models for a set of spatially coupled DC and FCS load flexibilities to achieve dimension reduction for easier embedding into current power system operation and planning optimization models, respectively [6][8], which are similar to the existing virtual power plant (VPP) modeling of traditional flexible resources [9]. An aggregation model for multiple sets of spatially coupled DC load flexibilities has also been proposed in [10]. These aggregation models emulate a VPP model with multi-port accesses.

Note that spatially coupled DC and FCS load flexibilities are disparate in spatial scales. Specifically, spatially coupled DC load flexibilities generally have relatively large spatial scales. It can be observed according to the geographical distribution of DCs owned by one Internet-service company, such as Google, where a set of DCs are widely geo-distributed for low latency and high reliability. Differently, considering that a driver has multiple FCSs to choose from in an origin-destination pair usually occurs in an urban transportation system, spatially coupled FCS load flexibilities have relatively small spatial scales. In other words, spatially coupled DC load regulation is usually operative both in helping alleviate congestions of transmission and distribution power systems. Spatially coupled FCS load regulation is usually operative in distribution power systems but inoperative in transmission

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power systems. This implies that the joint optimization of spatially coupled DC and FCS load flexibilities is necessary in case the distribution power system optimization is considered. The detailed physical interpretation for the necessity of the joint optimization is given in Section II, where the extra improvement can be achieved compared to the individual optimization.

However, a demand response approach that considers the cooperation of spatially coupled DC and FCS load flexibilities is rarely studied. This means that the optimal solution will not make full use of DC and FCS load regulations. In addition, the essence of the joint optimization is the aggregation and dispatch of multiple sets of spatially coupled load flexibilities with disparate spatial scales. One of the main challenges for this aggregation is how to deal with multiple spatial coupling constraints that are disparate in spatial scales. To the best of our knowledge, there are few of these aggregation modeling methods.

Thus, we propose a joint optimization method for spatially coupled DC and FCS load flexibilities to facilitate the full use of this type of new flexibility in this study. The main contributions of this paper are listed as follows.

(1) A physical interpretation for the necessity of the joint optimization of spatially coupled DC and FCS load flexibilities is presented.

(2) An aggregation model for multiple sets of spatially coupled DC and FCS load flexibilities is proposed. The proposed aggregation model captures their heterogeneity in spatial scales, achieves compatibility with varied power system optimization scopes, and emulates a VPP model with multi-port accesses. The proposed aggregation model gives a precise and concise mathematical relationship for the load regulation capacity among multiple sets of DCs and FCSs, which is the key contribution of this paper.

(3) A coordinated expansion planning model of transmission and distribution systems considering the joint optimization of spatially coupled DC and FCS load regulations, is presented to illustrate the application of the proposed aggregation model.

The remainder of this paper is given as follows.

II. Physical Interpretation for Joint Optimization

The physical interpretation for the joint optimization of spatially coupled DC and FCS load flexibilities is illustrated in Fig. 1. Fig. 1 shows that the extra improvement can be achieved with the joint optimization compared to the individual optimization due to their disparate spatial scales.

Specifically, Fig. 1 shows the congestion management process with spatially coupled DC and FCS load flexibilities. A set of DCs is connected to different buses of a transmission power system and a set of FCSs is connected to different buses of a distribution power system. The distribution power system is connected to a bus of the transmission power system, and a DC is connected to a bus of the distribution power system.

As shown in Fig. 1 (a), congestion occurs both in the transmission and distribution power systems. Fig. 1 (b) shows that spatially coupled DC and FCS load regulations are implemented to alleviate congestion. Three scenarios are included. In Scenario 1, spatially coupled DC load flexibilities are dispatched individually in the transmission power system first, and then spatially coupled FCS load flexibilities are dispatched in the distribution power system. In case the DC load connected to the distribution power system is downward regulated, and an increase in the DC downward adjustment corresponds to a slight congestion management cost for the transmission power system, the approach in Scenario 1 will result in the meaningless excessive FCS load regulation and the more increased total travel cost of the transportation system. In Scenario 2, spatially coupled FCS load flexibilities are dispatched individually in the distribution power system first, and then spatially coupled DC load flexibilities are dispatched in the transmission power system. This will also result in a meaningless excessive FCS load regulation, in case the DC load connected to the distribution power system is downward regulated. In Scenario 3, spatially coupled DC and FCS load flexibilities are dispatched jointly, which corresponds to the minimum total congestion management costs. In other words, it has that extra improvement can be achieved with the joint optimization compared to the individual optimization due to their disparate spatial scales. Fig. 1 (c) shows that congestion both in the transmission and distribution power systems has been eliminated through spatially coupled DC and FCS load regulations.

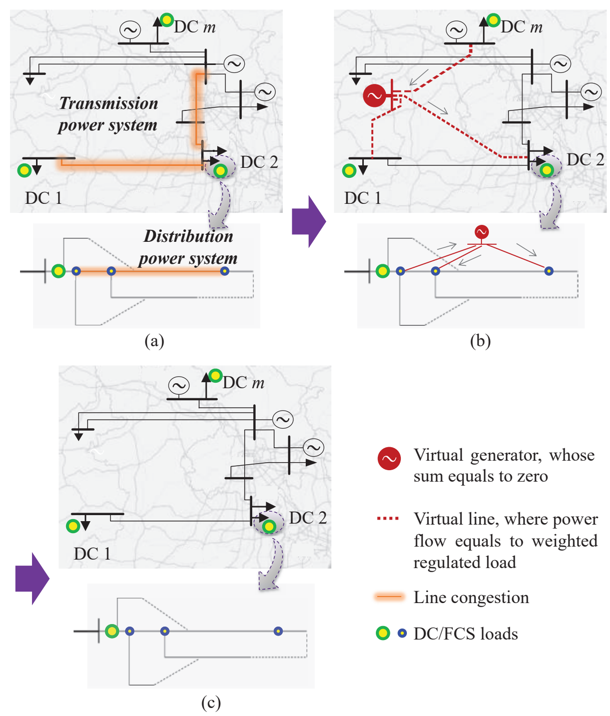

Fig. 1. Congestion management process: (a) Congestion occurs; (b) Congestion management through spatially coupled load flexibility dispatch; (c) Congestion is eliminated.

III. Aggregation Modeling Method

A. Aggregation Model for One Set of Spatiall Coupled DC or FCS Load Flexibilities

Based on [6] and [8], the aggregation model for one set of DC or FCS load flexibilities can be uniformly formulated in (1) and (2). Here, τ_{smt} is a continuous decision variable, representing the load regulation of DC m or FCS m belonging to set s in time window t. Eq. (1) describes the range of each DC or FCS load regulation capacity. In (1), β^{D}_{smt} and $-\beta^{U}_{smt}$

represents the maximum downward and upward DC *m* or FCS *m* load regulation capacities, respectively, which are related to the workload or traffic flow distribution before regulation and service capacity. Eq. (2) describes the spatial coupling of load regulation capacity among the multiple DCs or FCSs belonging to the same set. In (2), the sum of the weighted load regulations is zero, demonstrating that any single DC or FCS load reduction results in an increase in other DC or FCS loads. η_{sm} , the weighting factor, is related to the power consumption difference among the DCs or FCSs.

$$-\beta_{smt}^{U} \le \tau_{smt} \le \beta_{smt}^{D}, \forall s, m, t \tag{1}$$

$$\sum_{m} \eta_{sm} \tau_{smt} = 0, \forall s, t \tag{2}$$

In addition, the approximate load regulation cost model of one set of DCs or FCSs is formulated in (3). In (3), ϖ_{st} represents the total DC or FCS load regulation cost belonging to set *s* in time window *t*. α_s represents the unit DC or FCS load regulation cost belonging to set *s*.

$$\varpi_{st} = \alpha_s \sum_{m} |\tau_{smt}|, \forall s, t \tag{3}$$

B. Aggregation Model for Multiple Sets of Spatially Coupled DC and FCS Load Flexibilities

The aggregation model for multiple sets of spatially coupled DC and FCS load flexibilities is formulated in (4)-(6).

$$\sum_{sm \in n} -\beta_{smt}^{U} \le \tau_{nt}^{A} \le \sum_{sm \in n} \beta_{smt}^{D}, \forall n \in \Pi, t \tag{4}$$

$$\sum_{sm \in 0} -\beta_{smt}^{U} \le \tau_{0t}^{A} \le \sum_{sm \in 0} \beta_{smt}^{D}, \forall t \tag{5}$$

$$\eta_0 \tau_{0t}^{A} + \sum_{n} \eta_n \tau_{nt}^{A} = 0, \forall t \tag{6}$$

Specifically, let Π denote the power system optimization scope, where multiple electrical zones $n \in \Pi$ are included. The electrical zone outside Π is recorded as electrical zone 0 . For example, in a transmission power system congestion management scenario, Π can be a transmission power system, and the scope of n can be a node in a transmission power system, which covers a distribution power system. If in a distribution power system congestion management scenario, Π can be a distribution power system, and the scope of n can be a node in a distribution power system.

Eq. (4) describes the range of aggregated spatially coupled load regulation capacity in each electrical zone within the power system optimization scope. In (4), τ_{nt}^{A} represents the load regulation in electrical zone $n \in \Pi$ in time window *t*. The correlation between τ_{nt}^{A} and τ_{smt} is constrained by (7). As shown in (7), it can be found that in case a set of spatially coupled DC or FCS load flexibilities $\$$, where $\forall \$m \in n$ and $\forall \eta_{\$m} = 1$, the contribution of $\sum_{\$m} \tau_{\$mt}, \forall t$ to τ_{nt}^{A} is zero. That is, spatially coupled load flexibilities with relatively small spatial scales, are inoperative in helping alleviate congestion in relatively large power system scope.

$$\tau_{nt}^{A} = \sum_{sm \in n} \tau_{smt}, \forall n \in \Pi, t \tag{7}$$

Eq. (5) describes the range of aggregated spatially coupled load regulation capacity in the electrical zone outside the power system optimization scope. In (5), τ_{0t}^{A} represents the load regulation in electrical zone 0 in time window *t*. The correlation between τ_{0t}^{A} and τ_{smt} is constrained by (8).

$$\tau_{0t}^{A} = \sum_{sm \in 0} \tau_{smt}, \forall t \tag{8}$$

Eq. (6) describes the spatial coupling of load regulation capacity among multiple electrical zones. In (6), η_0 and η_n are the approximate weighting factors of τ_{0t}^{A} and τ_{nt}^{A}, which can be set as the average value of $\eta_{sm \in 0}$ and $\eta_{sm \in n}$, respectively.

In addition, the approximate aggregated load regulation cost model of multiple sets of DCs and FCSs is formulated in (9). In (9), ϖ_t represents the total DC and FCS load regulation cost in time window *t*. α_0 and α_n are the approximate unit load regulation cost of τ_{0t}^{A} and τ_{nt}^{A}, which can be set as the average value of $\alpha_{sm \in 0}$ and $\alpha_{sm \in n}$, respectively.

$$\varpi_t = \alpha_0 \left|\tau_{0,t}^{A}\right| + \sum_{n} \alpha_n \left|\tau_{n,t}^{A}\right|, \forall t \tag{9}$$

Note that τ_{nt}^{A} and τ_{0t}^{A} are continuous decision variables in (4)-(6) and (9). In addition, the proposed aggregation models are mainly used for ex-ante evaluation and dispatch of spatially coupled DC and FCS load flexibilities. The details are simplified in the modeling for a concise mathematical form and thus a clear physical meaning. The error caused by simplification, as well as other forecast errors, will be eliminated in real-time load tracking through parameter correction and other load regulation methods considering the uncertainty in the data and transportation systems. Besides, load regulation cost model can use other approximations in a scenario that is for the maximum social welfare.

IV. Joint Optimization in Power System Expansion Planning

A coordinated expansion planning model of transmission and distribution systems considering the joint optimization of spatially coupled DC and FCS load regulations is presented in this section. The problem determines the subset of generators and lines, within a set of candidates. Specifically, the objective function is formulated in (10), which is to minimize the total annualized expansion planning costs, where F_1 and F_2 represent annualized transmission and distribution power system expansion planning costs, respectively. $Y_{g^T}^{G}, Y_{l^T}^{L}, Y_{g^D}^{G}, Y_{l^D}^{L}$ are decision variables. $Y_{g^T}^{G}, Y_{l^T}^{L}$ represent installation status of candidate generator $g^T \in \Theta^{TC}$ and candidate line $l^T \in \Xi^{TC}$ in the transmission power system, respectively; $Y_{g^D}^{G}, Y_{l^D}^{L}$ represent installation status of candidate generator $g^D \in \Theta^{DC}$ and candidate line $l^D \in \Xi^{DC}$ in the distribution power system, respectively; where 1 if installed, and 0 otherwise.

$$\min_{Y_{g^T}^{G}, Y_{g^T}^{L}, Y_{g^D}^{G}, Y_{g^D}^{L}} F_1 + F_2 \tag{10}$$

Constraints consist of the following three parts.

Part 1: Related to F_1, including the formulation of F_1 in (11), binary constraints of decision variables $Y_{g^T}^{G}, Y_{l^T}^{L}$, and operation constraints in the transmission power system. Binary constraints and common operation constraints including power flow constraints, line flow and generation limits, and load curtailment limits, can be consulted [6]. Spatially coupled load regulation limits in transmission power system operation are formulated in (12)-(15).

Eq. (11) describes the total annualized transmission power system cost, including investment cost for added generators and lines, operation cost represented by generation cost, load curtailment cost, and spatially coupled load regulation cost. $\Theta^T \supseteq \Theta^{TC}$ is set of generators in the transmission power system, including candidate and existing generators. C^G and C^L are annualized capital costs of an expanded generator and line, respectively. $P^{G\max}$ and $P^{L\max}$ are the maximum capacity of a generator and line, respectively. L is length of a line. ω_k is probability of operation scenario k. O^G is unit operation cost of a generator. O^D is unit curtailment cost of a load. d^T is load d in the transmission power system. P^G is dispatched capacity of a generator. P^D is curtailment of a load (except spatially coupled loads). ϖ^T is spatially coupled load regulation cost in transmission power system operation. In (11), $Y^G_{g^T}, Y^L_{l^T}, P^G_{g^T,kt}, P^D_{d^T,kt}$ are control variables, and ϖ^T_{kt} is controlled through controlling $\tau^A_{n^T,kt}$.

$$F_1 = \sum_{g^T \in \Theta^{TC}} C^G_{g^T} P^{G\max}_{g^T} Y^G_{g^T} + \sum_{l^T \in \Xi^{TC}} C^L_{l^T} P^{L\max}_{l^T} L_{l^T} Y^L_{l^T} + \sum_t \sum_k \omega_k \left(\sum_{g^T \in \Theta^T} O^G_{g^T} P^G_{g^T,kt} + \sum_{d^T} O^D_{d^T} P^D_{d^T,kt} + \varpi^T_{kt} \right) \tag{11}$$

Eqs. (12)-(15) describe spatially coupled load regulation limits in transmission power system operation, where subscript k is omitted. Let Π^T denote the transmission power system scope, where multiple electrical zones $n^T \in \Pi^T$ are included. The electrical zone outside Π^T is recorded as 0^T. Eq. (12) describes the range of spatially coupled load regulation capacity in each electrical zone within the transmission power system. Eq. (13) describes the range of spatially coupled load regulation capacity in the electrical zone outside the transmission power system. Eq. (14) describes the spatial coupling of load regulation capacity among the multiple electrical zones in transmission power system operation. Eq. (15) describes total spatially coupled load regulation cost in transmission power system operation.

$$\sum_{sm \in n^T} -\beta^U_{smt} \le \tau^A_{n^T,t} \le \sum_{sm \in n^T} \beta^D_{smt}, \forall n^T \in \Pi^T, t \tag{12}$$

$$\sum_{sm \in 0^T} -\beta^U_{smt} \le \tau^A_{0^T,t} \le \sum_{sm \in 0^T} \beta^D_{smt}, \forall t \tag{13}$$

$$\eta_{0^T} \tau^A_{0^T,t} + \sum_{n^T} \eta_{n^T} \tau^A_{n^T,t} = 0, \forall t \tag{14}$$

$$\varpi^T_t = \alpha_{0^T} \left| \tau^A_{0^T,t} \right| + \sum_{n^T} \alpha_{n^T} \left| \tau^A_{n^T,t} \right|, \forall t \tag{15}$$

Part 2: Related to F_2, including the formulation of F_2 in (16), binary constraints of decision variables $Y^G_{g^D}, Y^L_{l^D}$, and operation constraints in distribution power system. Binary constraints, and common operation constraints including power conservation constraints, generation limits, dis-flow constraints, and load curtailment limits, can be consulted [11]. Spatially coupled load regulation limits in distribution power system operation are formulated in (17)-(20).

Eq. (16) describes the total annualized distribution power system cost, including investment cost for added generators and lines, operation cost represented by electricity purchasing cost from the main grid, generation cost, load curtailment cost, and spatially coupled load regulation cost. $\Theta^D \supseteq \Theta^{DC}$ is set of generators in the distribution power system, including candidate and existing generators. λ is unit electricity purchasing cost from the main grid. i is starting node of link $l^D \in \Xi^D$, where $\Xi^D \supseteq \Xi^{DC}$ is set of lines in the distribution power system, including candidate and existing lines. π is set of nodes connected to the main grid. ϖ^D is spatially coupled load regulation cost in distribution power system operation. In (16), $Y^G_{g^D}, Y^L_{l^D}, P^L_{l^D,kt}, P^G_{g^D,kt}, P^D_{d^D,kt}$ are control variables, and ϖ^D_{kt} is controlled through controlling $\tau^A_{n^D,kt}$.

$$F_2 = \sum_{g^D \in \Theta^{DC}} C^G_{g^D} P^{G\max}_{g^D} Y^G_{g^D} + \sum_{l^D \in \Xi^{DC}} C^L_{l^D} P^{L\max}_{l^D} L_{l^D} Y^L_{l^D} + \sum_t \sum_k \omega_k \left(\lambda_t \sum_{i \in \pi} P^L_{l^D,kt} + \sum_{g^D \in \Theta^D} O^G_{g^D} P^G_{g^D,kt} + \sum_{d^D} O^D_{d^D} P^D_{d^D,kt} + \varpi^D_{kt} \right) \tag{16}$$

Eqs. (17)-(20) describe spatially coupled load regulation limits in distribution power system operation, where subscript k is omitted. Let Π^D denote the distribution power system scope, where multiple electrical zones $n^D \in \Pi^D$ are included. The electrical zone outside Π^D is recorded as 0^D. Eq. (17) describes the range of spatially coupled load regulation capacity in each electrical zone within the distribution power system. Eq. (18) describes the range of spatially coupled load regulation capacity in the electrical zone outside the distribution power system. Eq. (19) describes the spatial coupling of load regulation capacity among the multiple electrical zones in distribution power system operation. Eq. (20) describes the total spatially coupled load regulation cost in distribution power system operation.

$$\sum_{sm \in n^D} -\beta^U_{smt} \le \tau^A_{n^D,t} \le \sum_{sm \in n^D} \beta^D_{smt}, \forall n^D \in \Pi^D, t \tag{17}$$

$$\sum_{sm \in 0^D} -\beta^U_{smt} \le \tau^A_{0^D,t} \le \sum_{sm \in 0^D} \beta^D_{smt}, \forall t \tag{18}$$

$$\eta_{0^D} \tau^A_{0^D,t} + \sum_{n^D} \eta_{n^D} \tau^A_{n^D,t} = 0, \forall t \tag{19}$$

$$\varpi^T_t = \alpha_{0^D} \left| \tau^A_{0^D,t} \right| + \sum_{n^D} \alpha_{n^D} \left| \tau^A_{n^D,t} \right|, \forall t \tag{20}$$

Part 3: Consistency constraint of spatially coupled load regulation between transmission and distribution power system operations, which is formulated in (21).

$$\eta_{n^T} \tau^A_{n^T,t} = \sum_{n^D \in n^T} \eta_{n^D} \tau^A_{n^D,t}, \forall n^T \in \Pi^T, t \tag{21}$$

V. Case Studies

A. Settings

Assume an IEEE 24-bus transmission power system, where Bus 2 connects an IEEE 33-bus distribution power system. A set of three DCs is connected to Buses 2, 6, and 22 of the transmission power system. A set of three FCSs is connected to buses 3, 6, and 16 of the distribution power system. The DC in Bus 2 is also connected to bus 2. It is assumed that the transmission power system will be expanded as the total load increases to 6,270 MW in upcoming years, where the baseline of each DC load is 91.25 MW. Other parameters about the transmission power system and DCs are as in [6]. The distribution power system except the DC load will be expanded as the total active/reactive load increases to 7,430 kW/4,600 kVar, where the baseline of FCS loads is 1,900, 1,550, and 1,550, respectively. The capacity of two lines between buses 1–2 is 90 and 6 MW, respectively. Other parameters about the distribution power system and FCSs are as in [8]. Simulations are performed in MATLAB environment and YALMIP toolbox.

B. Results and Analysis

Fig. 2 shows the transmission and distribution power system expansion results in three cases. Neither spatially coupled DC or FCS load regulation is considered in Case 1. Cases 2-3 consider spatially coupled DC and FCS load regulations, which are individual optimizations in Case 2 while joint optimizations in Case 3. The proposed models are applied in Case 3.

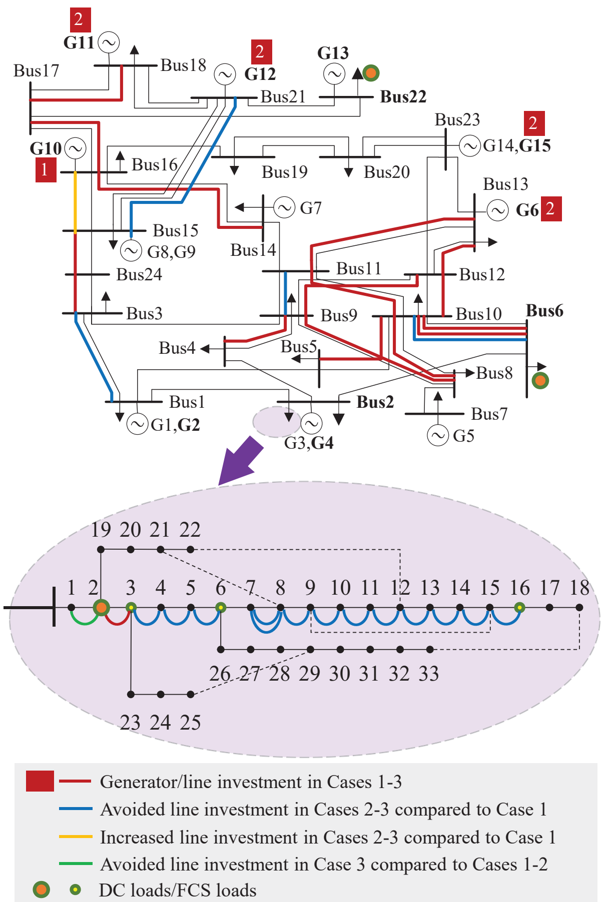

Fig. 2. Generator and line investment results in Cases 1-3.

It has that the transmission and distribution power system expansions in Cases 2-3 are significantly reduced compared to Case 1. This implies that the spatially coupled DC and FCS load flexibilities can be successfully implemented to partially prevent transmission and distribution power system expansions, respectively. It also has that the distribution power system expansion in Case 3 is further reduced compared to Case 2, where the total distribution power system expansion cost is further reduced by 8%. This implies that the joint optimization of spatially coupled DC and FCS load flexibility has extra improvement compared to the individual optimization. Accordingly, the efficiency of the proposed aggregation model for the joint optimization has been verified.

VI. Conclusions

This study has proposed a joint optimization method for spatially coupled DC and FCS load flexibilities to facilitate their full use. The following conclusions are drawn:

(1) The joint optimization of spatially coupled DC and FCS load flexibilities can be successfully implemented to further prevent power system expansion and lower the expansion cost compared to the individual optimization. In our case, the total distribution power system expansion cost is further reduced by 8%.

(2) The proposed aggregation model for multiple sets of spatially coupled DC and FCS load flexibilities is efficient for the joint optimization. Specifically, the proposed aggregation model captures their heterogeneity in spatial scales, achieves compatibility with varied power system optimization scopes, and emulates a VPP model with multi-port accesses.

In our future work, the proposed models will be extended to study the utilization of spatially coupled load flexibilities.

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