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Modeling Joint Optimal Transmission Switching and Bus Splitting via Reduced Bus–Branch and Bus–Breaker Representations

Jiajun Han, Rabab Haider†

***Abstract*—Transmission network reconfiguration is essential for congestion management, yet substation reconfiguration (bus splitting) is often overlooked due to its modeling complexity. This paper proposes a unified framework to jointly optimize line switching and bus splitting. To maintain computational tractability, we employ two complementary representations: a bus-branch representation that models bus splitting as a line outage and power transfer; and a more detailed bus-breaker representation that captures flexibility from substation reconfigurations beyond the bus-branch representation. We demonstrate that the bus-branch optimal solutions effectively guide the modeling of branch-to-busbar assignment policies of the bus-breaker representation, further enhancing performance under high loading levels with tight switching budgets. Numerical experiments on IEEE test systems confirm that this joint approach provides significant flexibility compared to line switching alone.**

***Index Terms*—Transmission Network Reconfiguration, Optimal Transmission Switching, Bus Splitting.**

I. Introduction

Transmission network reconfiguration (TNR) represents a challenging yet promising domain in power system operations. By treating the grid topology as a control variable, operators can reroute power flows to relieve congestion and accommodate variability in load patterns and renewables [1]. TNR actions involve both *line switching* (opening transmission lines) and *bus splitting* (reconfiguring substations through internal breaker actions).

Optimal Transmission Switching (OTS), as formalized by Fisher et al. [2], is a well-established approach for selecting an optimal set of in-service lines. However, OTS only modifies existing edges of the network graph. In contrast, bus splitting [3] provides *substation-level* flexibility by changing the electrical connectivity among incident branches, busbars, and device attachments. This added flexibility comes at a significant modeling cost: bus splitting alters the network graph by creating additional nodes, and its feasible actions depend on the underlying substation topology and breaker configurations, alongside power flow constraints. Consequently, prior work relies on detailed node-breaker representations that model the substation configuration at the level of individual breakers and busbars [4], or reduced bus-branch representations that capture only a subset of possible bus split actions [5].

This note addresses the challenge of modeling bus splits by developing a unified framework for transmission network reconfiguration with both line switching and bus splitting. To model different types of bus splits efficiently, we use two complementary reduced representations: a bus-branch model and a bus-breaker model. First, we show that in the bus-branch model, a subset of bus splits is equivalent to opening a line and introducing an induced power transfer [5], enabling a tractable Mixed Integer Linear Program (MILP) formulation. This representation, however, is limited to configurations that can be expressed through a single line outage. Second, to capture bus splitting actions that cannot be represented in the bus-branch model, we extend the framework via a tractable bus-breaker model. We further leverage the bus-branch optimal solutions to guide the configuration of the bus-breaker model. Case studies on IEEE test systems demonstrate the potential for TNR — especially bus splitting — to relieve grid congestion, improving power flow feasibility and economics under high loading levels with tight switching budgets. Our results show the scalability of our joint OTS and bus splitting framework.

II. Modeling Bus Splitting

Consider a transmission grid where $\mathcal{N} := \{1, ..., N\}$ is the set of substations and $\mathcal{K} := (i, j) \subset \mathcal{N} \times \mathcal{N}$ is the set of transmission lines, and each line $k \in \mathcal{K}$ connects an ordered substation pair (i, j). Each substation has an internal configuration, composed of energized busbars, to which other components (loads, generators, lines) are connected, and circuit breakers that connect the busbars. In the base configuration, all energized busbars are connected, i.e., the adjoining breakers are closed. When needed for operations, maintenance, or during a fault, the topology of the substation can be changed by opening/closing breakers—called bus splitting. Fig. 1 shows a bus splitting event where solid squares represent closed breakers and hollow squares represent open breakers. The original busbar i is split into two busbars after opening the top right breaker. The resulting two busbars, denoted as i and i', are physically co-located but electrically isolated. We consider three levels of substation modeling:

Node-Breaker Representation: Reflects the layout of substations, explicitly representing busbars, breakers, and their interconnections, as in Fig 1. This is the most detailed representation of the physical substation.

Bus-Breaker Representation: A simplified model assuming a substation configuration with exactly two busbars connected by a bus coupler and a breaker. Each line or attached load/generator is connected to only one of the two busbars.

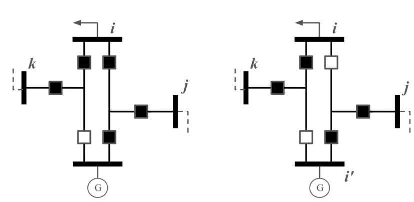

Fig. 1: (Left) Original node-breaker model. (Right) Updated model with an additional breaker open [5] .

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Bus-Branch Representation: Represents each substation as a single node. This is prevailing in power systems optimization, including OTS problems.

The bus-branch representation has the advantage of being widely adopted in power flow and results in smaller problem instances, compared to the full node-breaker representation: in the latter, with typically 4-6 breakers per substation, at least 4-6 binary variables must be co-optimized to select the configuration of a single substation. An equivalent model of bus splitting in the bus-branch representation was derived in [3], modeled as a line outage followed by a power transfer. This is illustrated in Fig. 2. The left diagram shows a substation i connected to two neighbors j and k. The center shows the post-split system with the creation of a new bus i', and the allocation of the load to i and generator to i'. The right shows the equivalent model [3] where the bus splitting event is modeled as the outage of line (i, j) and a power transfer of the generation from bus i to bus j. We denote this as a *single-switch bus split*.

Fact 1 [3]: Consider the post-split system of a bus split, producing bus i and i', where a single neighbor j connected by line (i, j) and an injection p_i are assigned to the new bus i'. This is modeled equivalently as the opening of a switch on line (i, j) and an additional power transfer of p_i from i to j.

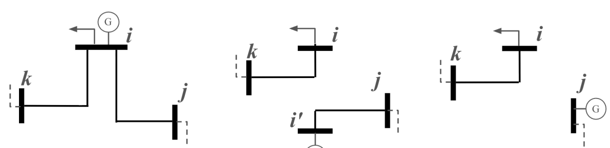

Fig. 2: (Left) Original bus-branch model. (Middle) Updated model due to bus split. (Right) Equivalent bus-branch model [3].

When the connectivity degree (the number of incident branches) of the target bus is at most three, a single-switch bus split is sufficient to represent any resulting configuration. Figure 3 shows an example of bus i with connectivity degree three, where two lines (i, m) and (i, n) are switched out simultaneously and the attached load and generator are transferred from i to i'. This is equivalent to a single-switch split in which only line (i, j) is opened and no power transfer is introduced, as shown in Fig. 4. The resulting post-switch bus-branch representations are equivalent.

Fact 2: For any bus i whose connectivity degree is at most three, there exists an equivalent single-switch bus split that can represent the outcome of any multiple-switch bus split.

However, the equivalent bus-branch model is limited to configurations that can be modeled with a single line outage. When the connectivity degree exceeds three, a bus split with multiple simultaneous line outages cannot be generally represented by an equivalent single-switch split in the bus-branch representation. To capture such configurations, we introduce a bus-breaker representation. Fig. 5 shows a bus with connectivity degree four, where a multiple-switch bus split that opens (i, m) and (i, n) is equivalently modeled as opening the busbar coupler in the corresponding bus-breaker representation with an additional power transfer. We denote this as a *multiple-switch bus split*. Modeling a substation via the bus-breaker representation requires an assignment policy, describing how incident power lines are assigned to busbar i and i'. In this we observe a fundamental symmetry: assigning a subset of incident lines to busbar i' is mathematically equivalent to retaining that subset at i and moving the complement to i'. Note that generators and loads do not need an assignment policy, as the power transfer accounts for this as an output of the optimal topology. The assignment policy is further discussed in the Sec. IV.

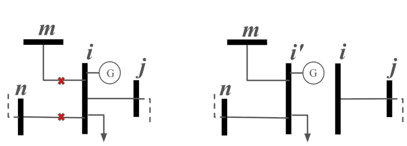

Fig. 3: (Left) Original bus-branch model. (Right) Updated bus-branch model after a multiple-switch bus split that opens (i, m) and (i, n) and transfers the attached load and generator from i to i'.

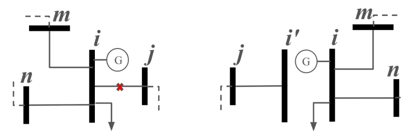

Fig. 4: (Left) Original bus-branch model. (Right) Updated bus-branch model after a single-switch bus split that opens (i, j) with no power transfer.

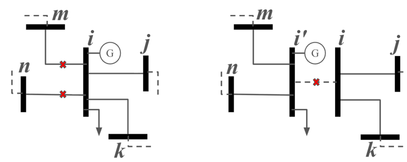

Fig. 5: (Right) Equivalent bus-breaker model for the (left) original bus-branch model containing a multiple-switch bus split that opens (i, m) and (i, n) and transfers the attached load and generator from i to i'.

Fact 3 (Bus-Breaker Model Robustness): In a bus-breaker model, the assignment policy determines the partition of incident lines between the two busbars. The assignment of one subset to busbar i versus busbar i' does not affect feasibility or optimality.

III. Joint OTS and Bus Splitting Modeling

The standard DC-OTS formulation [2] minimizes total generation cost subject to DC power flow physics and line switching decisions. Decision variables include P_g, the active power output of generator g, and $z_k \in \{0, 1\}$ the line status (1 if line $k = (i, j)$ is in service, 0 if switched out). Power flow on the resulting topology is described by θ_i, the voltage phase angle at bus i, and f_k, the active power flow on line k. For each line k, let b_k denote its susceptance and $f_k^{\min}, f_k^{\max}$ its flow limits. Generator cost coefficients are c_g, and bus demands at bus i are d_i. Let $\mathcal{G}$ be the set of generators and $\mathcal{G}_i \subseteq \mathcal{G}$ be the set of generators located at bus i.

The DC-OTS is augmented with bus splitting as follows. We consider a candidate set of substations that can be split, $\Theta \subseteq \mathcal{N}$, defined as the set of buses with a single generator and one or no loads. Let N_i denote the neighbor set of bus i. We define three specific power transfer modes during the single-switch bus split on Θ, indexed by $w \in \{1, 2, 3\}$, representing the combination of devices transferred from bus i to j:

- $w = 1$: Transfer the load
- $w = 2$: Transfer both load and generation
- $w = 3$: Transfer the generator

The selection of transfer mode is defined by $x_{ij,w} \in \{0, 1\}$, which equals 1 if transfer mode w is activated from bus i to neighbor j. The net injection transferred across the split at bus i toward j is denoted by $\Delta_{ij} \in \mathbb{R}$. The TNR problem is formulated as:

$$\min_{\substack{P_g, z_k, f_k, \theta_i \\ x_{ij,w}, \Delta_{ij}, w_k}} \quad \sum_{g \in \mathcal{G}} c_g P_g \tag{1a}$$

$$\text{s.t.} \quad \theta^{\min} \leq \theta_i \leq \theta^{\max}, \quad \forall i \in \mathcal{N} \tag{1b}$$

$$P_g^{\min} \leq P_g \leq P_g^{\max}, \quad \forall g \in \mathcal{G} \tag{1c}$$

$$f_k^{\min} z_k \leq f_k \leq f_k^{\max} z_k, \quad \forall k \in \mathcal{K} \tag{1d}$$

$$b_k(\theta_i - \theta_j) - f_k + (1 - z_k) M_k \geq 0, \quad \forall k \in \mathcal{K} \tag{1e}$$

$$b_k(\theta_i - \theta_j) - f_k - (1 - z_k) M_k \leq 0, \quad \forall k \in \mathcal{K} \tag{1f}$$

$$\sum_{k \in \mathcal{K}} (1 - z_k) \leq \mathcal{B} \tag{1g}$$

$$\sum_{w \in \{1,2,3\}} x_{ij,w} + \sum_{w \in \{1,2,3\}} x_{ji,w} \leq 1 - z_k, \quad \forall \{k \in \mathcal{K} | i, j \in \Theta\} \tag{1h}$$

$$\sum_{j \in N_i} \sum_{w \in \{1,2,3\}} x_{ij,w} \leq 1, \quad \forall i \in \Theta \tag{1i}$$

$$\Delta_{ij} = x_{ij,1}(-d_i) + x_{ij,2}(-d_i + P_g) + x_{ij,3} P_g, \forall i \in \Theta \tag{1j}$$

$$\sum_{k \in \mathcal{K}(\cdot,i)} f_k - \sum_{k \in \mathcal{K}(i,\cdot)} f_k + \sum_{g \in \mathcal{G}_i} P_g - \Delta_{i,N_i} + \sum_{j \in N_i \cap \Theta} \Delta_{ji} = d_i, \ \forall i \in \Theta \tag{1k}$$

$$f_k^{\min} \leq \Delta_{ij} \leq f_k^{\max}, \quad \forall \{k \in \mathcal{K} | i, j \in \Theta\} \tag{1l}$$

Constraints (1b)–(1f) represent standard DC power flow physics with line switching using big-M method. The big-M values are selected based on the line parameters. The budget constraint (1g) limits the total number of open lines from any TNR action to a budget $\mathcal{B}$. Constraint (1h) enforces that a bus splitting at either end of line $k = (i, j)$ is only valid if the physical line is switched open ($z_k = 0$). This formulation allows a bus split even when only one end of the line belongs to the candidate set Θ. Constraint (1i) limits each candidate bus $i \in \Theta$ to be split only once. The power transfer is defined in (1j) based on the selected mode w. The bilinear terms $x_{ij,2} P_{g \in \mathcal{G}_i}$ and $x_{ij,3} P_{g \in \mathcal{G}_i}$ can be linearized using McCormick's inequalities [6]. Constraint (1k) maintains nodal power balance. The power transfer is bounded by the capacity of the open line in (1l).

To prevent network islanding, we introduce Single-Commodity Flow (SCF) [7] constraints. We introduce an auxiliary flow variable $w_k \in \mathbb{R}$ for each line, a root bus r, and let $U := |\mathcal{N}| - 1$:

$$-U z_k \leq w_k \leq U z_k, \quad \forall k \in \mathcal{K}, \tag{2a}$$

$$\sum_{k \in \mathcal{K}(\cdot,i)} w_k - \sum_{k \in \mathcal{K}(i,\cdot)} w_k = \begin{cases} U, & i = r, \\ -1, & i \neq r, \end{cases} \quad \forall i \in \mathcal{N}. \tag{2b}$$

Constraints (2a)–(2b) ensure that all energized buses form a connected graph.

Formulation (1), while originally derived for the bus-branch model (limited to single-switch bus splits), extends naturally to multi-switch bus splits using the bus-breaker model by including bus couplers as a zero-impedance line in set $\mathcal{K}$.

IV. Numerical Experiments and Results

We evaluate the joint OTS and bus splitting framework against benchmarks including DC-**OPF** (optimal power flow, no TNR actions) and only **OTS** (with SCF). We evaluate both single-switch bus splitting (**OTS+SBS**) and multiple-switch bus splitting (**OTS+MBS**), to show the enhanced feasibility and economic performance from TNR with bus splitting. Experiments use IEEE 14-, 30-, and 118-bus cases from PGlib-OPF [8]. All MILPs are implemented in Julia and solved with Gurobi to a 0.1% optimality gap.

A. Congestion Relief from Bus Splitting

We evaluate **OTS+SBS** and benchmarks under varying loading with switching budget of $\mathcal{B} = 10$. In Tables I–III, *Loading Level* uniformly scales all demands (e.g., at 130%, all loads are multiplied by 1.3). *Reserve* is the remaining generation headroom, and *OPF*, *OTS*, and *OTS+SBS* report optimal generation costs. The "–" denotes infeasibility of the formulation. We include *Reserve* to highlight that the observed infeasibility is driven by network congestion, which can be relieved by TNR, rather than insufficient generation capacity.

Across all tests with a fixed switching budget $\mathcal{B}$, **OTS+SBS** matches **OTS** under light loading but outperforms it as loading increases: SBS (i) improves economics when **OTS** remains feasible but the network is congested (e.g., 30-bus at 110–115%, 118-bus at 130–135%), and (ii) restores feasibility in heavily loaded regimes where both **OPF** and **OTS** fail (e.g., 14-bus at 130%, 30-bus at 125%). All cases are solved to a 0.1% gap within 30 seconds, indicating that the joint model is tractable and that even single-switch bus splitting can provide substantial congestion relief.

TABLE I: Performance on 14-bus System (150MW Line Limit, $\mathcal{B} = 10$).

Loading Level (%)	Reserve (MW)	OPF ($)	OTS ($)	OTS+SBS ($)
100	140.0	2596	2051	2051
115	101.2	–	2359	2359
130	62.3	–	–	**3252**

TABLE II: Performance on 30-bus System ($\mathcal{B} = 10$).

Loading Level(%)	Reserve(MW)	OPF($)	OTS($)	OTS+SBS($)
100	79.6	7472	5639	5639
110	51.3	8781	7919	**7118**
115	37.1	–	8540	**7857**
125	8.8	–	–	**9336**

TABLE III: Performance on 118-bus System ($\mathcal{B} = 10$).

Loading Level(%)	Reserve(MW)	OPF($)	OTS($)	OTS+SBS($)
100	2273.0	93152	93104	93103
130	1000.4	135652	129771	**129746**
135	788.3	–	136633	136600

TABLE IV: Performance of different $\mathcal{B}$ on 14-bus System (150 MW line limit, 135% loading).

$\mathcal{B}$	OTS+SBS($)	Decisions	OTS+MBS($)	Decisions
1	–	–	3558	**(2→15):{2, 22.1}**
2	3626	**(2→5)** **(2→3):{2, 26.5}**	3537	(4→9) (2→15):{2, 20.8}
3	3579	(2→5) (4→7) (2→3):{2, 23.5}	3531	(4→9) (9→10) (2→15):{2, 20.8}

Extending the TNR actions to include multiple-switch bus splits (**OTS+MBS**) can achieve additional cost savings and congestion relief: reconfiguring a substation with high connectivity changes the grid topology and resulting power flows more significantly (e.g., decouples more voltage angle constraints [9]). The proposed bus-breaker representation models this flexibility while maintaining computational tractability of the resulting MILP. Tables IV–VI compare the performance of **OTS+SBS** and **OTS+MBS** at a high loading level under varying switching budgets $\mathcal{B}$. The tables report objective values and the corresponding *Decisions*, where "$(i \to j)$" denotes opening line (i, j), and "$(i \to j) : \{w, \Delta\}$" denotes bus splitting of bus i along the connection to j with mode w and induced power transfer Δ_{ij} (MW). As expected, **OTS+MBS** improves both feasibility and economics for a given $\mathcal{B}$, and can provide better performance with fewer switching operations, as compared to **OTS+SBS**. Notably, under these stressed conditions, **OTS** is either infeasible (14- and 30-bus) or significantly more expensive (118-bus) than joint OTS and bus splitting.

B. Modeling MBS using SBS Optimals

TNR actions often involve similar sets of substations. An illustrative example is shown on the 14-bus system (Table IV and Fig. 6). At $\mathcal{B} = 2$, **OTS+SBS** opens $(2, 5)$ and applies an SBS action on $(2, 3)$ with mode 2, decoupling bus 3 and 5 from bus 2. When MBS is permitted, only a single reconfiguration action is needed: bus 2 is split to decouple from buses 3 and 5. These observations suggest that the assignment policy required for the bus-breaker representation can be guided by the **OTS+SBS** optimal decisions. In the example of the 14-bus system, the corresponding assignment policy for bus 2 in the bus-breaker model is as follows: split bus 2 into busbars $\{2, 15\}$, assign lines $(2, 5)$ and $(2, 3)$ to busbar 15, and introduce a coupler $(2, 15)$. In **OTS+MBS** at $\mathcal{B} = 1$, the coupler $(2, 15)$ is opened. With a different assignment policy, the same benefits cannot be achieved: assigning $(2, 3)$ and $(2, 4)$ to busbar 15 instead would render **OTS+MBS** infeasible at $\mathcal{B} = 1$. Thus, an arbitrary assignment policy may restrict potential MBS actions by precluding desired separations. A similar pattern is observed on the 30- and 118-bus systems (Tables V–VI) for $\mathcal{B} \in \{1, 2\}$. By leveraging the **OTS+SBS** optima to guide the assignment policies, **OTS+MBS** can mimic incident line separations in the bus-branch representation and thereby improve feasibility and/or cost.

V. Conclusion

This paper develops a unified framework that jointly considers line switching and bus splitting. We introduce bus-branch and bus-breaker representations to model bus splitting, and formulate TNR as a tractable MILP. Simulations on IEEE feeders

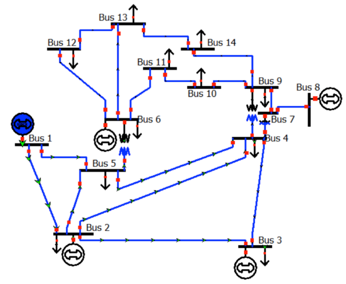

Fig. 6: Diagram of IEEE 14-bus system [10].

TABLE V: Performance of different $\mathcal{B}$ on 30-bus System (125% loading).

$\mathcal{B}$	OTS+SBS($)	Decisions	OTS+MBS($)	Decisions
1	9494	(2→4):{1, -27.1}	9403	**(2→31)**
2	9349	**(2→4)** **(2→5):{2, 56.5}**	9336	(2→31) (4→12)
3	9336	(2→4) (12→16) (2→5):{2, 56.1}	9336	(2→31) (4→12) (2→4):{1, -27.1}

show that bus splitting can improve feasibility and reduce cost, particularly under high loading and tight switching budgets. Future work will further explore line-to-busbar assignment in the bus-breaker model and test on industry-scale networks.

VI. AI Usage Disclosure

AI tools were used only for grammar and style editing, not for research tasks (e.g., literature review, modeling, or coding).

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TABLE VI: Performance of different $\mathcal{B}$ on 118-bus System (110% loading).

$\mathcal{B}$	OTS+SBS($)	Decisions	OTS+MBS($)	Decisions
1	104987	(80→81):{3,509}	104089	**(49→119)**
2	104549	**(49→69)** **(49→47):{2,110}**	103979	(49→119) (103→105):{1,-25}
3	104210	(49→69) (49→47) (46→45):{2,-10}	103959	(49→119) (103→105):{1,-25} (105→106):{2,-34}

I. REVIEW #139A

A. Paper summary

The paper proposes a unified framework to jointly model optimal transmission switching (OTS) and bus splitting for transmission network reconfiguration. Two complementary formulations are introduced: a bus–branch representation, where bus splitting is represented through line outages and power transfers, and a more detailed bus–breaker formulation that captures additional flexibility associated with substation configurations. The resulting optimization problem is formulated as a mixed-integer linear program (MILP) and evaluated on several IEEE benchmark systems. The results indicate that jointly considering line switching and bus splitting can improve feasibility and reduce operating costs under stressed operating conditions.

B. Comments for authors

The paper studies the joint modeling of optimal transmission switching (OTS) and bus splitting for transmission network reconfiguration. The topic is relevant, as network reconfiguration is an important operational tool for congestion management and for increasing flexibility in power system operation. The manuscript is concise, clearly written, and well structured. The figures are clear and helpful in illustrating the modeling ideas, and the numerical experiments on standard IEEE test systems provide useful examples of the proposed framework.

The proposed modeling framework combines two complementary representations: a bus–branch formulation that captures bus splitting through line outages and power transfers, and a bus–breaker formulation that explicitly models substation configurations. This unified treatment is interesting and highlights the potential benefits of jointly considering line switching and bus splitting when addressing network congestion and stressed operating conditions.

That said, several aspects of the work would benefit from additional clarification. First, the literature already contains a number of approaches for modeling bus splitting and substation reconfiguration. While the proposed framework appears practical, the manuscript does not clearly explain how the proposed formulations differ from or improve upon existing approaches. A clearer discussion positioning the contribution relative to prior work would help readers better understand the novelty and added value of the proposed method.

Second, the MILP formulation relies on big-M constants, but the manuscript does not discuss how these parameters are selected or tuned. Since the choice of big-M values can significantly affect both numerical stability and computational performance, providing some explanation or guidelines would help ensure that the formulation can be reproduced and implemented reliably.

Third, there appears to be a possible inconsistency in Table III. In the 130% loading scenario, the reported cost for the OTS solution is higher than the OPF baseline. This seems counterintuitive and should be checked and clarified.

Finally, the paper does not report computational performance metrics for the proposed formulations. Since one of the motivations for introducing the bus–branch representation is computational tractability, it would be useful to provide information about solution times and solver performance, as well as a comparison between the different modeling choices.

Overall, the paper presents an interesting study on the joint modeling of transmission switching and bus splitting. Clarifying the novelty relative to existing literature, providing additional details on modeling parameters, verifying the reported results, and reporting computational performance metrics would strengthen the contribution.

C. Summarize your recommendation in one to two sentences

The paper studies an interesting and relevant problem and presents a clearly written framework for jointly modeling transmission switching and bus splitting. However, the contribution would benefit from clearer positioning with respect to existing literature and additional details regarding modeling parameters and computational performance.

— Salvador Pineda

II. REVIEW #139B

A. Paper summary

The paper develops an optimal transmission network reconfiguration approach that considers switching of transmission lines alongside bus-bar splitting options.

B. Comments for authors

The paper addresses an important problem and uses novel insights to simplify an otherwise very expensive computational task. While the technical approach seems reasonable in general, there are some unclear parts. The following comments can help improve the manuscript:

1) Since the formulation (1) is written for a single-step bus split, it would have helped to highlight the differences with respect to reference [5].

2) The discussion of Figure 3, leading up to Fact 2, is unclear. On the left panel of Figure 3, bus m and n are shown to get disconnected from bus i while in the right panel, they are still connected to the generator and load which were connected to bus i. Since Fact 2 reads correctly, I believe the confusion can be overcome by rephrasing the discussion and updating the figure.
3) Presumably, constraints (1b)-(1f) apply to all buses/lines, and not just to a particular bus i or branch k. The presentation should be made more precise where possible.
4) Section IV-B is an important portion of this work, advancing the developments over [5]. It would have helped if the discussion were more elaborate and comments were made on whether the intuition from a relatively small testcase can be relied upon as a general technique. Having said that, it is understandable that the page limit for this note limits the scope of expansion.

C. Summarize your recommendation in one to two sentences

The paper solves an important problem and features novel insights. It could have benefited from clearer exposition.

— Anonymous reviewer

III. Review #139C

A. Paper summary

The paper proposes a unified framework to model and optimize transmission topology operations with both line switching and substation reconfiguration (bus split). A novel bus-breaker model is introduced to circumvent the limitations of using bus-branch model in modeling bus split. Numerical examples on 14-, 30- and 118-bus systems demonstrate the effectiveness of the proposed framework.

B. Comments for authors

The paper identifies an important limitation in existing literature when it comes to modeling bus split in optimal transmission reconfiguration (OTR) problems. The existing equivalent model of ”line outage + power transfer” approach only works when one of the two buses to be split is incident to only one line. The proposed approach addresses this issue by extending the modeling capability of bus split to cases where the bus to be split has degree higher than three. The validity of the approach is demonstrated on several IEEE test cases with different loading conditions. As a notes paper, it tells a comprehensive story.

One clarification question is that it seems to me that the resulting optimization formulation is still based on the ”bus-branch” modeling philosophy where a bus split is modeled as the outage of a neighboring line and a power transfer. The power transfer can be viewed as Kron reduction, and when the newly split bus is incident to only one bus, the Kron reduction does not result in new connections among existing buses. However, when a new bus is connected to multiple buses, the reduction (or power transfer) of the bus results in the introduction of new lines among buses connected to the bus. It is not clear to me how this is addressed in the formulation.

In addition, it is mentioned at the end of Section III that the model extends naturally to multi-switch bus splits using the bus-breaker model by including bus couplers in the line set $\mathcal{K}$. However, since the line susceptance of the bus coupler is negligible, how exactly can this be modeled in the optimization formulation is not entirely clear to me.

C. Summarize your recommendation in one to two sentences

The paper identifies an important limitation in existing literature when it comes to modeling bus split in optimal transmission reconfiguration (OTR) problems. More clarifications on the bus-breaker modeling in the optimization formulation would be much appreciated.

— Bai Cui

IV. Brief response to reviewers (optional)

Reviewers: Thank you for your careful review. The comments raised are addressed below. Our future work will extend this note paper to generalize the model and heuristic to larger networks.

Review A

1) Prior works typically employ bus-branch (limited representation of substation reconfiguration, computationally tractable) or node-breaker (high fidelity, often computationally intractable) models for reconfiguration. To address limitations of existing models, we introduce a reduced bus-breaker model and formulate an MILP that jointly considers line switching and bus splitting while maintaining computationally tractability and preserving feasible topological actions including multi-switch bus splits.
2) The big-M values are selected based on the line parameters. This has been updated in the paper.

3) We thank the reviewer for identifying this issue. The inconsistency in Table III was caused by different optimality gap settings (Gurobi MIPGap) across runs. The table has been updated using the same MIPGap; the qualitative results remain the same.
4) All reconfiguration cases (OTS and OTS+MBS) are solved to a 0.1% gap within 30 seconds, showing the extended reconfiguration with bus splitting is a tractable formulation. This is reported at the beginning of Section IV.

Review B

1) Formulation (1) generalizes the model in [5] to multi-switch bus splitting using a bus-breaker representation, modeled as a zero-impedance bus coupler.
2) Fact 2 is shown in Figs. 3 and 4, where two different bus split events can be modeled equivalently. In Fig. 3, bus (j) is connected to substation (i). In Fig. 4, bus (m) and (n) are connected to the substation (i). Figure 4 has been updated to better communicate this configuration.
3) Yes, constraints (1b)–(1f) apply over the appropriate sets of buses and branches. The formulation has been updated accordingly.
4) Our preliminary results on the three test networks provide initial evidence that the approach can be generalized to larger networks. Our future work beyond this note paper will continue to develop this methodology.

Review C

1) Thank you for this clarification question. In the first case (split bus has a single incident bus), the bus-branch representation can be used, and emits the Kron reduction interpretation. In the second case (split bus has multiple incident buses), the reviewer is correct that the bus-branch representation cannot model this action without the introduction of a new line. This is the motivation for our proposed bus-breaker representation: Prior to any reconfiguration action, a substation with 4 or more neighbouring buses (call it substation i) is modeled with a bus coupler joining i and i' (see Fig. 5); splitting this bus is the "outage" of the bus coupler and a power transfer from i to i'. Powerlines incident to the original substation i (Fig 5 left) are assigned to either i or i' based on the heuristic developed in Section IV.B, where the optimal reconfiguration decisions of OTS+SBS are used to infer line assignment.
2) In the multi-switch bus split model, the bus coupler is modeled as a switchable zero impedance line. For experiments, the bus coupler is set to a very small reactance value (e.g., $x = 1e^{-5}$ p.u.) to approximate a zero-impedance.

V. Brief Summary of Changes Made to the Final Paper

1) Updated Table III to correct the inconsistency between the OPF and OTS results under the 130% loading scenario. The inconsistency was caused by different optimality gap settings (Gurobi MIPGap) across runs. The table has been updated using the same MIPGap; the qualitative results remain the same.
2) Revised formulation (1), constraints (1b)–(1f), to specify the appropriate sets of buses and branches.
3) The big-M values are selected based on the line parameters. This has been updated in Section III.
4) Updated Fig. 4 to clearly show Fact 2 (equivalent representation of a single switch bus split), differentiating from Fig. 3.
5) In the multi-switch bus split model, the bus coupler is modeled as a switchable zero impedance line. For experiments, the bus coupler is set to a very small reactance value (e.g., $x = 1e^{-5}$ p.u.) to approximate a zero impedance. This has been specified in Section III.