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Energy Reports 14 (2025) 1467–1478

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Optimization of topological reconfiguration by transmission line switching for damping inter-area oscillations in power systems

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ARTICLE INFO

Keywords:
Topological reconfiguration
Transmission switching
Small signal stability
Inter-area oscillations
Eigenvalue analysis
Multi-objective particle swarm optimization
Genetic algorithm

ABSTRACT

Intentional grid topology change is sometimes used in power system operations to control voltages, improve the net transfer capacities, and even to boost system reliability. As a consequence of topological change by transmission line switching, the power system may be subjected to inter-area oscillations which could impair system integrity in terms of small signal instability. This study has employed quadratic eigenvalue analysis to confirm that topological reconfiguration through transmission line switching can be used to control system voltages especially during high voltage regimes. It has further confirmed that topological reconfiguration when implemented without consideration of system stability, results in inter-area oscillations or in worst cases, in actual instability. This work has therefore proposed a method which uses multi-objective particle swarm optimization algorithm to optimize implementation of topological reconfiguration during voltage control to avoid inter-area oscillatory instability. In this proposed method, the optimization algorithm specifies which lines are to be switched off but at the same time improves small signal stability in the whole network. The proposed method has been tested in the IEEE 30-bus, IEEE 39-bus, and IEEE 68-bus models. The results indicate that when an optimized transmission switching is implemented, small signal stability is improved alongside voltage control, and can save power system operators from relying on intuition which is prone to human errors as they make operational decisions.

1. Introduction

The connectivity between power system components comprising of generating equipment, transformers, transmission lines, loads, etc. define power system topology. Power flows in an interconnected grid dictated by generation patterns, load/demand profiles and network topological architecture (Maas et al., 2007). Typically, large power systems involve directly connected synchronous generators interconnected by high voltage transmission systems. Power systems are subject to electromechanical oscillations, a tendency that arises from the law of conservation of energy, Kirchoff's law and synchronism (Byrne et al., 2016). These physical laws are manifested in form of inter-area oscillations (IAO) which exist between power generation centres that are coupled by weak transmission systems. The frequencies of these IAO are determined by the generators' and turbines' inertia as the rotating masses (Elizondo et al., 2018).

With high export and import of power via weak interconnectors, these oscillatory modes which are characterized by very low frequencies, typically less than 1 Hz cause swinging of a group of generators in one area against a group of other generators in another area. During this oscillatory process, there is exchange of kinetic energy between coherent groups of synchronous generators and when not contained, may cause inadvertent operation of protection equipment which could lead to cascade tripping and result in power system collapse (Kumar, 2013). The exchange of oscillatory energy may also result in de-rating of the transmission lines and thus limiting power transfer capability. These events can restrict market operations and they need to be carefully assessed (Prasertwong et al., 2010).

During power system operations, small signals may be excited even if damping devises are deployed in service hence, remedial actions that could involve topology change need to be engaged. These remedial actions change the equilibrium point (and hence the modal properties) at which the power system was linearized. Remedial actions which consist of operational interventions can therefore be used alongside the conventional damping controllers when the system oscillations are not adequately damped (Setareh et al., 2020).

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https://doi.org/10.1016/j.egyr.2025.06.050
Received 16 February 2025; Received in revised form 7 June 2025; Accepted 29 June 2025
Available online 28 July 2025

System operators sometimes perform intentional grid topology change to control voltage profiles, increase transfer capacity, and even improve system reliability. The minimum damping ratio is a critical parameter for ensuring the stability of power systems since it dictates the rate at which oscillations decay. When a certain type of swing occurs in a system with low damping ratio, it may lead to a limitation of power transfer capability or, worse, a growth in amplitude of the LFOs which could led to system collapse (Chompoobutrgool and Vanfretti, 2012). Acceptable standard values of damping ratio vary and they depend on factors such as the size and complexity of the power system; the types of generators and loads connected; and the regulatory requirements in a particular region. In the Mexican system, a damping ratio of at least 5% is the minimum acceptable value and any oscillation mode with a damping ratio less than this value is considered as a critical one and appropriate actions must be taken in order to improve the damping of such mode (Calderón-Guizar et al., 2017). According to Grebe et al. (2010), damping is adequate if all the electromechanical modes have a damping ratio of at least 5% but LFOs with damping ratio less than 3% indicate instability. In China, the damping ratio should be above 3% to assure SSS (Wang et al., 2015). In Cigré (1996) it is recommended that a minimum damping of 5% should be maintained in power networks. To ensure reliable operation of the system, the Western Electricity Coordinating Council (WECC) specifies a damping ratio of 4.5%, while other grid codes have a practice of a 5% threshold (Hedman et al., 2011).

Improved energy market operations have been realized by optimal network topological reconfiguration through transmission switching. This becomes prevalent especially with the deployment of renewable generation (Hedman et al., 2011). Topological changes are also common in power system operations due to routine maintenance requirements, faulty conditions, economic considerations and power reliability concerns.

Different types of control systems, such as PSSs, HVDC controls, and FACTS devices, can significantly improve the eigenvalues and hence the stability of power systems, but they have some limitations/challenges in their performance since their improper design or tuning can lead to adverse effects and therefore require a careful consideration of their control system parameters and interactions with the power system.

While HVDC systems can improve power transfer capabilities and have demonstrated good damping performance on particular oscillation modes, the modulation control for one mode may adversely impact the other IAO modes (Elizondo et al., 2018). Fast response controllers of line commutated converter-HVDC (LCC-HVDC) may lead to sub synchronous torsional interaction in nearby synchronous machines (Gao et al., 2017). Other negative impacts of HVDC include radio and telephone interference and effects on nearby HVAC systems like temporary over-voltages; low order resonances and long fault recovery times; requirements of large reactive power, inertia, short-circuit requirements and the potential for commutation failures especially the LCCs.

PSSs are designed to enhance damping of low-frequency oscillations (LFO) but its greatest challenge is the difficulty to adequately select and utilize signals with high robustness and observability as input signals in the control feedback loop (Chompoobutrgool and Vanfretti, 2012). High-speed excitation systems used to prevent the loss of synchronizing torque and hence improve transient stability tends to weaken the damping characteristics of LFOs (Shim et al., 2017). Therefore, there are tuning challenges with regard to balancing between synchronizing torque and damping torque due to the antagonistic effects of high-gain, fast-acting AVR and PSS control systems in response to transients and oscillations respectively (Elizondo et al., 2018). It is also noted that PSSs designed using local mode signals may not properly damp IAO oscillations because such oscillations involve generators that are geographically spread out in larger areas. In this context, phasor measurements units (PMU) play an important role in facilitating the design of wide-area damping controllers which require the use of remote signals. A challenge when using remote signals in damping controllers is the inherent communication delays, which may be due to network-induced delays, data dropout, etc. Meegahapola et al. (2020).

FACTS do improve system security by enhancing the transient stability limit; limiting short-circuit currents and overloads; managing cascading contingencies and damping electromechanical oscillations but their optimal placement in the power system is normally the greatest challenge. Although FACTS controllers can create satisfactory damping effects on IAO, they are not cost-effective when used only for damping control (Elizondo et al., 2018). Other challenges associated with FACTS include achieving smooth and fast responses; power transfer constraints due to thermal limitations; non-linear nature resulting in harmonics and resonance conditions.

Previous works have demonstrated that topological reconfiguration can damp oscillatory modes. In Setareh and Parniani (2018), the use of restructuring corrective actions is proposed to damp IAO. The effect of line switching on damping IAO is investigated. The method changes topology of the network by transmission line switching and this helps in stabilizing IAO. It is noted that this method does not indicate exactly the prevailing conditions that necessitate or motivate line switching (like overvoltage control or overload of some components of the system).

Using Monte Carlo analysis, the impact of topology on power system transient and frequency stability is studied in Ebrahimzadeh et al. (2019). Contingencies are created at random on every network for testing both transient and frequency stability. It was revealed that creating many interconnections can improve dynamic stability of the system and hence increase the transfer capability that is available for trading in an electric network. This study focuses on transient and frequency stability and the methodology involves use of only synthetic networks where contingencies are created randomly. The study did not use standard network models and did not also propose a structured methodology for creating contingencies.

The impact of SSS on system reconfiguration is analyzed in Ridwan et al. (2019) where faulty conditions are simulated by using a power system simulation program to represent the real conditions, and the results of oscillations are analyzed by using the Prony method. System reconfiguration is developed by changing the generator supply direction and the setting of PSS to analyze the stability. No modal analysis (frequency-based) was conducted since only Prony analysis in time domain has been used. It is also not very straightforward to determine specifically the impact of topological change on SSS, since the study also involved the use of other control methods like adjustment of PSS.

In Thakar et al. (2019), a capability curve perspective of the effect of P-Q limits on microgrid reconfiguration is studied. The study investigates the impact of system reconfiguration on: voltage profiles, reactive power reserves, system losses and radiality. It was observed that optimal reconfiguration reduces power losses and improves power quality which leads to customer satisfaction. This research work only concentrated on generation injection and other controls at the distribution and reticulation levels to effect topology change, but did not consider transmission level switching as a means of topological reconfiguration.

Dependence on network structure on small-disturbance voltage stability of power systems is investigated in Huang et al. (2019) by defining the weighted load connectivity (WLC) as an index for stability of network structures. From Monte Carlo simulations it was discovered that the network with a larger value of WLC has a tendency for maintaining small-disturbance voltage stability (SDVS). It should be noted that Monte Carlo methods have some limitations and challenges, such as the trade-off between accuracy and computational cost and the verification/ validation of results.

In Dheer et al. (2016), the effect of reconfiguration and mesh on SSS margin of a droop-based islanded microgrid is investigated. This is a very interesting study which involves statespace eigenvalue analysis and root locus to establish the effects of reconfiguration and network type on SSS. The study revealed that optimally reconfigured

networks based on loss minimization and loadability maximization still are prone to SSS problem, hence it is advisable to keep it as a constraint while undertaking reconfiguration. The study however lacks a universal methodology for conducting topological adjustment and would be more complete if an algorithm that implements an optimization between reconfiguration and SSS improvement was proposed.

The manner and nature of influence on IAO modes and mode shapes by topology changes have been studied in Chen et al. (2011). It was pointed out that topological reconfigurations have considerable impact on the SSS of a power system and that while some topological changes negatively affect SSS, there were however some reconfigurations that result in an improved damping ratio. Therefore, there is need for more studies in this area to reveal how these reconfigurations could be employed to enhance SSS in addition to the conventional control schemes, such as PSS.

After commissioning of the Huai-Hu ultra-high Voltage Alternating Current Project (UHVAC), low frequency oscillations (LFO) behavior was studied in the East China Power Grid (Wang et al., 2015) where it was observed that during maintenance of the transmission lines in some regions in which the grid structure is not too strong, the risk of poorly-damped LFO could increase. The study however only considered a maintenance situation as a reason for topology change. In Hedman et al. (2009), it is observed that power system operations involve switching transmission equipment to: (a) improve voltage profiles, (b) enhance transfer capacity, (c) benefit from topology change during emergency conditions and (d) for cutting costs by incorporating transmission switching into the optimized dispatch. There is however no stability considerations in this optimization study.

After realizing that the connection of Turkey to the European Network of Transmission System Operators for Electricity (ENTSOE-E) system in 2010 resulted in a new east–west mode where generators in Portugal and Spain oscillate against those in Turkey, it was recommended that topological reconfiguration by reinforcement of the existing power systems would be necessary to avoid stability problems (Benasla et al., 2018). A SSS constrained voltage control optimization is still lacking and is needed to compliment the reinforcement approach that was recommended in this study.

In Dong et al. (2024), it was observed that high output from inverter-based resources (IBR) stress the power system and makes it prone to SSS. The study recommended that strengthening power systems by topological changes would raise the short circuit ratio which in turn would improve SSS. This research work employed phasor-domain methodology to study power system oscillations in high renewable power systems and considered oscillations emanating only from disturbances caused by line cascade tripping events after faults, which is basically a transient stability study, devoid of SSS analysis.

Severe contingencies of a multiple nature in electric power systems are identified by a methodology presented in Donde et al. (2005). In this study, a small set of transmission lines are identified whose switching off from operational service would require load shedding to avoid potential cascading events that could lead to blackouts. A nonlinear optimization framework is employed, although in a static sense, meaning that the practical impact of the identified events could be different if the study could consider dynamics.

It is acknowledged that while topological changes can affect both voltage regulation and SSS, the magnitude of these effects can vary significantly depending on the specific configuration changes and the operating conditions of the power system. Some reconfigurations might lead to suboptimal voltages in certain areas but improving SSS in others and vice versa. This scenario may require some trade-off between voltage regulation and SSS improvement. The proposed optimization methodology for topological reconfiguration performs the double task of regulating voltages and improving SSS at the same time through the multi-objective algorithm.

The literature review identifies some research gaps that can be summarized as follows:

a. some studies focused on transient and frequency stability without SSS study and used only synthetic networks where contingencies were created in a random manner instead of using standard test models and then propose a structured methodology for creating contingencies;
b. in some studies, no eigenvalue analysis has been conducted to give information related to the modal behavior of the networks including interaction of various synchronous machines (e.g. swinging);
c. no straightforward impact of specifically topological change on SSS is revealed since some studies included adjustment of PSS, change of generation injection and other controls at the distribution and reticulation levels without considering transmission level switching;
d. relying on some methods like the Monte Carlo that have inherent limitations and challenges like accuracy and computational cost, and the verification and validation of results;
e. there is no SSS-constrained voltage control for a holistic approach to power system control.

The major differences between the proposed method in this study and the other methods so far implemented are two-fold:

a. it is first formulated from a common practice in power system operations where the main driver of topological reconfiguration is voltage control, which is usually done without consideration of SSS. The impact of topological reconfiguration on voltage is then studied using quadratic eigenvalue analysis;
b. both genetic algorithm (GA) and multi-objective particle swarm optimization (MOPSO) algorithms have been used to conduct an optimization process that is aimed at optimizing topological reconfiguration for voltage control while considering SSS.

The novelty in this proposed methodology in relation to the other research work in the area, especially (Setareh and Parniani, 2018)–(Donde et al., 2005) involve the following:

a. by quadratic eigenvalue analysis, the impact of topological reconfiguration on SSS during voltage control is revealed;
b. an optimized topological reconfiguration method (by transmission line switching) for voltage control which is constrained by SSS using MOPSO is proposed. In this proposed method, the optimization algorithm, performs the twin functions of specifying which (and the number of) lines to be switched off for voltage control and improving SSS. It is not only limited to specific lines and buses as is the norm by power system operators when relying on intuition/experience to make operational decisions, but it focuses on the whole network;
c. trends in research and academic work concerning transmission network reconfiguration are presented.

The remainder of this paper is organized as follows: the theoretical framework is presented by detailing the process of eigenvalue analysis in Section 2. Section 3 is dedicated to the research methodology and presentation of the proposed optimization method. In Section 4, the results and discussions are presented while Section 5 gives the conclusion and recommendation.

2. Theoretical framework

Due to the advantage of linearization of power system models, the eigenvalue analysis has been employed in conducting the SSS study. Another strength of eigenvalue method is that it makes available information such as various weak modes, the dominant state variables associated with those modes and sensitivity of those modes to parameter variation. It further allows investigation of the dynamic behavior of the system under different frequencies (modes). Modal analysis

therefore shows the coherent generator groups swinging against each other and identifies the generators that have a significant contribution to the phenomena (Grebe et al., 2010). An electrical network consists of an interconnection of different electrical elements. Based on some assumptions, all the dynamical components of this network (generators, dynamic loads, regulators etc.) can be described by differential and algebraic equations (DAE) (Dussaud, 2015). Modal analysis of a linear time invariant system in terms of the eigen properties of state matrix A is shown in Eqs. (1) and (2) (Ghandhari, 2011).

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \tag{2}$$

where $\dot{\mathbf{x}}$ refers to $n \times 1$ vector of the derivative of the state variables; $\mathbf{x}$ is $n \times 1$ vector of the state variable matrix; $\mathbf{u}$ is the $m \times n$ input matrix; $\mathbf{y}$ is the $n \times 1$ output vector; $\mathbf{A}$ is the system matrix; $\mathbf{B}$ is the input matrix; $\mathbf{C}$ is the output matrix; and $\mathbf{D}$ is the feedforward matrix.

The eigenvalues of state matrix $\mathbf{A}$ are given by the nx solutions of $\lambda = \lambda_1, \ldots, \lambda_{nx}$ which satisfy

$$\det(\mathbf{A} - \lambda\mathbf{I}) = -\sigma_i \pm j\omega_{pi} \tag{3}$$

where $\det(\cdot)$ denotes determinant, $\mathbf{I}$ is the identity matrix. The eigenvalues may be real or complex. An eigenvalue λ_i is normally related to a particular oscillation mode of the system.

Complex eigenvalues appear as conjugate pairs, where each pair relates to an oscillatory mode of which the ith mode is expressed by Eq. (4).

$$\lambda_i = -\sigma_i \pm j\omega_{pi} \tag{4}$$

The level of stability is given by the real component (σ_i) while the frequency of oscillation is given by the imaginary component (ω_{pi}) as given by the expression in Eq. (5) and the damping ratio is consequently given by Eq. (6).

$$f = \frac{\Im\{\lambda\}}{2\pi} = \frac{\omega}{2\pi} \tag{5}$$

$$\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \approx -\frac{\sigma}{\omega} \tag{6}$$

The stability of an equilibrium point can be determined based on the eigenvalues of the system by applying Lyapunov's theorem (Eakeley et al., 2002), i.e. a negative real eigenvalue represents a decaying mode whereas a positive real eigenvalue corresponds to a monotonic instability i.e.:

i. when the eigenvalues have negative real parts, the oscillation decays and the original system is asymptotically stable. A system is therefore stable if all eigenvalues are located in the left half on the s-plane for a specific operating regime.
ii. when at least one of the eigenvalues has a positive real part, the oscillation grows and the original system is unstable.
iii. when the eigenvalues have real parts equal to zero, the amplitude of the oscillation remains at a constant and it is not possible on the basis of first approximation to say anything in general.

The further the real part of the eigenvalue is from the origin of S-plane, the higher the damping ratio of the oscillatory modes and the power system is more stable. A CIGRE taskforce about oscillations in networks recommends a minimum damping ratio of 5% (Tractebel Engie, 2017). Any non-zero vector v_i^r which satisfies

$$\mathbf{A}\mathbf{v}_i^r = -\lambda_i \mathbf{v}_i^r \tag{7}$$

is termed the right eigenvector of $\mathbf{A}$ corresponding to the eigenvalue λ_i. Similarly, any non-zero vector $\mathbf{v}_i^l$ which satisfies

$$\mathbf{A}\mathbf{v}_i^l = -\lambda_i \mathbf{v}_i^l \tag{8}$$

is termed the left eigenvector of $\mathbf{A}$ corresponding to the eigenvalue λ_i.

The measures of those two properties i.e. right eigenvector and left eigenvector are the controllability and observability, respectively. If a mode is neither controllable nor observable, the feedback between the output and the input will have no effect on the mode (Mandour et al., 2014).

Mode shape which is given by the right eigenvector can provide additional information on SSS including the interaction of coherent generator groups. This information helps in determining the appropriate damping schemes required (Chompoobutrgool, 2012).

2.1. Problem statement

Relying only on intuition and experience of the power system operators when undertaking grid topological reconfiguration through transmission line switching to control voltages can subject the power system to inter-area oscillations which could impair system integrity in terms of IAOs. This work develops an optimization methodology that is constrained by small signal stability from operations perspective.

3. Research methodology

3.1. Impact of topological reconfiguration on SSS

Power systems analysis toolbox (PSAT) (Milano, 2005) has been used together with Simulink® (MathWorks, Natick, Massachusetts, United States) to study the impact of topological reconfiguration on inter-area oscillatory behavior, focusing on both IEEE 30-bus and IEEE 39-bus models. In accordance with (Beyza and Yusta, 2021), these networks were chosen because:

a. they can be applied to many studies with a reasonable solution time;
b. their results are adequately representative of other networks.

This study involved:

i. creating various scenarios of topological changes in the network by taking some transmission lines out of service (switching off) with the aim of controlling high voltage situations as is normally done during system operations.
ii. conducting eigenvalue analysis for every scenario to establish correlation between the topological change and instances of IAO (i.e. appearance of unstable eigenmodes and undesirable damping ratios).
iii. monitoring the bus voltage behavior in the entire network model arising from the topology change

The following assumptions were made in this study.

a. the total transmission line capacities in the models are not violated by switching off some lines. This is to ensure that the study only focuses on SSS without mixing it with transfer capacity constraints.
b. topological reconfiguration by line switching is the only available means of mitigating high voltages during these regimes.

Conceptually, the aim was to: (a) demonstrate that at operational level, topological reconfiguration by line switching controls system voltages but compromises SSS (first research problem); and (b) test whether the proposed methodology is effective in optimizing topological reconfiguration to improve inter area oscillatory performance (second research problem).

3.2. Optimization problem

A metaheuristic optimization algorithm such as genetic algorithm (GA), differential evolution (DE), particle swarm optimization (PSO),

simulated annealing (SA) etc. can be used in this work because: (a) the problem is nonlinear and requires linearization of the system matrix with every topological reconfiguration before computing the eigenvalue (b) the PSAT simulator can be used along with the algorithms.

Any algorithm can be used in research cases like this work provided that it: (a) can handle integer decision variables and; (b) can optimize multi-objective problems. Since the transmission system plays a very critical role in the power system and considering the emerging complexity in power interconnections, enhanced penetration of renewable energy resources and the increased enforcement of regulations in the power sector, it was important to demonstrate how two algorithms perform in the solution of this problem. The selected algorithms are variants of GA and PSO which are widely applied in stochastic optimization applications and which use different approaches to select solutions during each iteration.

The variants of GA and PSO used were non-dominated sorting genetic algorithm III (NSGA-III) and competitive mechanism based multi-objective particle swarm optimizer (CMOPSO), which is a version of multi-objective PSO (MOPSO) that explores more diverse solutions (Deb and Jain, 2013; Zhang et al., 2018; Coello and Lechuga, 2002). Both variants use non-dominated sorting learning strategy that avoids favoring one objective over the other, leading to a diverse set of optimal solutions on the Pareto front. This strategy reduces the likelihood of the solution getting stuck in a local minimum by broad exploration of the space containing feasible solutions. Additionally, these two algorithms can be encoded to work with integer decision variables. Further, NSGA-III and CMOPSO are designed for fast convergence.

Formulation of the multi-objective optimization problem and approach are presented in Section 3.3.

3.3. Optimization approach

An open source evolutionary optimization platform called PlatEMO was used to solve the optimization problems (Tian et al., 2017). While implementing voltage control by way of topological reconfiguration through transmission line switching, the ultimate objective was to: (a) minimize the maximum real part of the eigenvalue and (b) maximize the minimum damping ratio of linearized IEEE 30-bus and IEEE 39-bus models by topological reconfiguration through a multiobjective optimization process. The objective functions together with associated constraints were formulated as shown in Eqs. (9) to (15).

a. **Objective functions**

1. Referring to Eq. (4) which gives the mathematical model of the complex eigenvalue, its real part can be employed to formulate the first objective function as:
   Minimizing the maximum real part of eigenvalues, σ_{max} (to improve SSS)

$$\underset{\mathbf{l}}{\text{minimize}} \quad \sigma_{\max} \tag{9}$$

   where **l** is the vector listing the lines that are switched off in a network.
2. In the same manner, referring to Eq. (6) which gives the mathematical model of the damping ratio, it can be used to formulate the second objective function as:
   Maximizing the minimum damping ratio, ζ_{min} (to improve SSS)

$$\underset{\mathbf{l}}{\text{minimize}} \quad -\zeta_{\max} \tag{10}$$

b. **Constraints**

1. The minimum damping ratio, $\zeta_{\min}$, must be non-negative (to ensure SSS is not violated)

$$\zeta_{\min} \geq 0 \tag{11}$$

2. The maximum real part of the eigenvalues, $\sigma_{\mathbf{max}}$, must be in the left half of the s-plane (to ensure SSS is not violated)

$$\sigma_{\max} \geq 0 \tag{12}$$

3. Range of allowable bus voltage regulation, $V_r = (V_{bus} - V_{base})/V_{base}$ (to ensure voltage stability is not violated)

$$V_r(\min) \leq V_r \leq V_r(\max) \tag{13}$$

   where V_{bus} is the bus voltage, V_{base} is the bus voltage in the baseline case, and $V_r(\min)$ and where $V_r(\max)$ are the minimum and maximum allowable voltage regulation.
4. range of number of lines to be switched off, l (to avoid violation of N-2 contingency criterion and transfer capacity)

$$l_{\min} \leq l \leq l_{\max} \tag{14}$$

5. Limit of voltage phase angle difference, δ_i, between either ends of any line i in the system (to avoid angle instability)

$$|\delta_i| \leq \delta_{\max} \tag{15}$$

Most utility or power pool grid codes specify steady-state transmission voltage bandwidth at ±10% or 0.1 p.u. (to avoid: a) dielectric and thermal stresses on equipment insulation during prolonged high voltages, and b) voltage collapse during low voltage situations), hence the choice of values used for $V_r(\min)$ and $V_r(\max)$. System operators usually rely on intuition to make decisions on which lines to switch off to control voltages, but in this proposed method, the optimization algorithm specifies which and the number of lines to be switched off in a way that does not violate SSS for the whole of the network and not focusing only on specific lines and buses. To avoid small signal instability, the maximum phase angle difference is typically 30°. Exceeding this angle can lead to unstable power oscillations due to the increased potential for power swings between generators when small disturbances occur. In this algorithm, at least one transmission line needs to be switched off to facilitate voltage control and the maximum number of lines is specified as two to conform with a stringent N-2 contingency criterion usually adopted by some utility grid codes. It means that any contingency which results in the loss of two transmission lines should not jeopardize the stability or synchronism of the system. Of course, any number of transmission lines may still be specified depending on the system mesh degree. Therefore, the actual values of the parameters used during the simulations were $V_r(\min) = -0.1$, $V_r(\max) = 0.1$, $l_{\min} = 1$, $l_{\max} = 2$ and $\delta_{\max} = 30°$.

3.3.1. Flowcharts

The flowchart shown in Fig. 1(a) presents the optimization approach. Solution updates, **L**, for each generation, i, are obtained using NSGA-III and CMOPSO. For each member of the surviving solutions, topological reconfiguration and SSS analysis is done to evaluate the corresponding objective functions. For each i, feasibility of the **L** updated using either of the two algorithms is ensured by imposing the constraints.

For both algorithms, the population is set to $s = 100$ and the total number of generations to run is set to $I = 50$. The number of decision variable is set to $N = 3$, with the first being a binary decision variable and the remaining two are integers. Since $l_{\min} = 1$ and $l_{\max} = 2$, the choices we have to make for every decision are:

i. is the second line going to be switched off (binary 0) or on (binary 1) (which represents the first binary decision variable), and
ii. what are the identities of the first and the second lines (which represent the second and third decision variables).

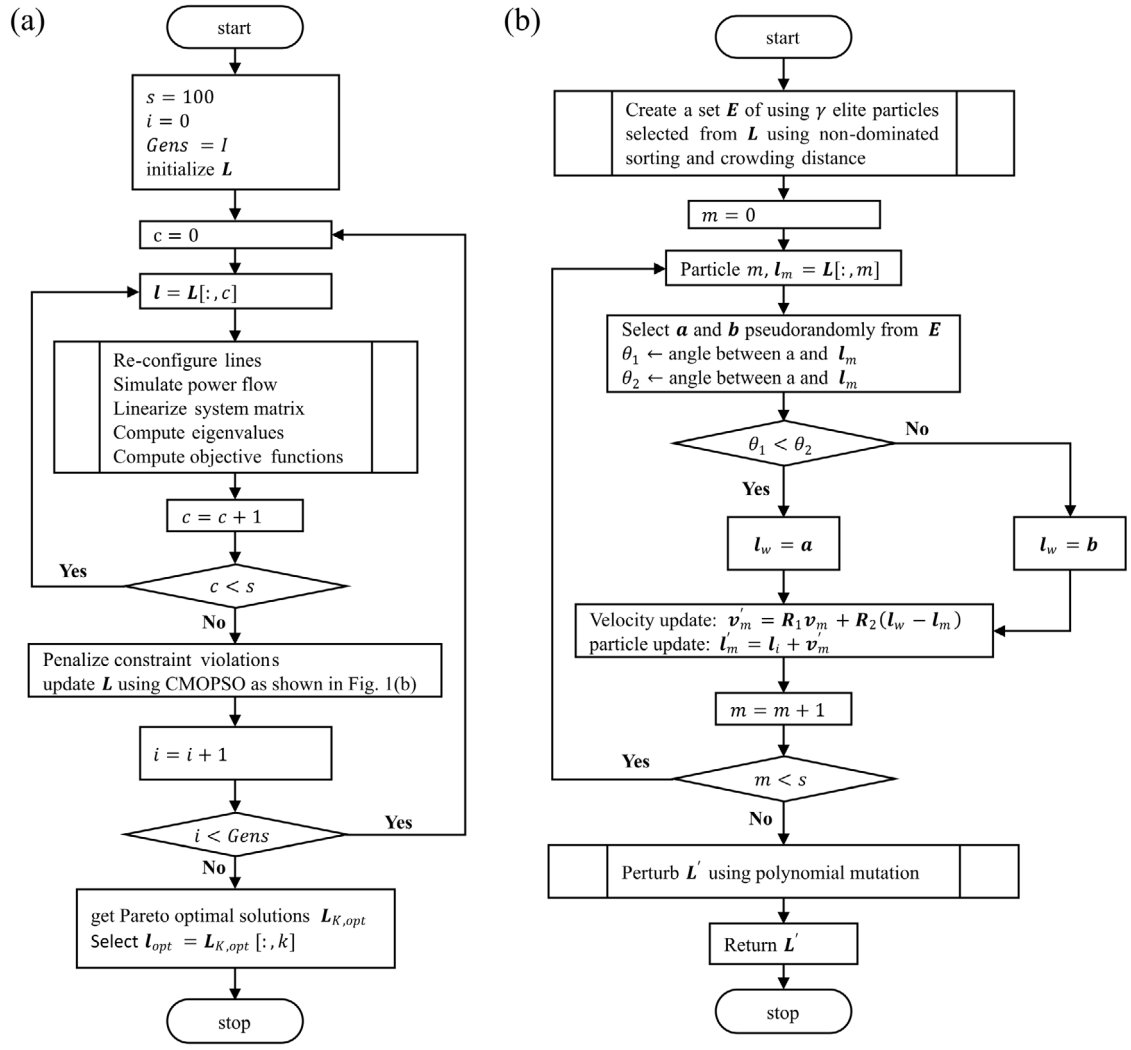

Fig. 1. Flowcharts showing the proposed optimization approach (a) and an iteration in the CMOPSO optimization routine (b). The iterative process for each generation penalizes the objective functions corresponding to the particles that violate the constraints set in Eqs. (9) to (15), then a metaheuristic optimization algorithm updates the next generation. The population size $s = 100$, the maximum number of generations $I = 50$. The only parameter required by the CMOPSO routine in (b) is γ, which is set to a recommended value of 10 in PlatEMO (Zhang et al., 2018; Tian et al., 2017). Optimal solutions can be selected from the Pareto front by prioritizing one of the two objective functions.

The lines are selected from the set of all lines in the network, and each is labeled using a unique integer number, starting from 0 and ending at $N_{\text{lines}} - 1$, where N_{lines} is the total number of lines in the network.

The optimal solution $\mathbf{l}_{\text{opt}}$ is selected from a set of K Pareto optimal solutions. The two objective functions are not in conflict because improving either generally leads to an improvement of the other. The solutions, if forming a Pareto front, are close to each other. Upon running the optimization algorithms, we noted that the solutions were not changing significantly beyond 30 generations, so we kept the maximum number of generations at $I = 50$.

Fig. 1(b) presents what happens in a single iteration of the CMOPSO algorithm. CMOPSO improves its solution space exploration ability over canonical PSO-based approaches by building upon competitive swarm optimization (CSO), which uses competition between particles in the current swarm to update new particle positions instead of tracking historical behavior of the particles (Cheng and Jin, 2015). The competition between particles and the avoidance of historical information improves CSO's ability to avoid local optima and it reduces the computation burden involved with tracking historical results.

The CMOPSO algorithm adopted for this work has three major steps; (1) selection of elite particles, (2) particle competition, and (3) particle learning (Zhang et al., 2018). Only one parameter, γ, requires tuning and it gives the number of elite particles to be selected from the entire population. A value of $\gamma = 10$ has been recommended and implemented in the platform we used for optimization (Cheng and Jin, 2015; Tian et al., 2017). The recommended value is especially helpful for problems that yield solutions with localized Pareto fronts, since these are the cases that are most affected by the choice of γ. The set $\mathbf{E}$ made of γ elite particles selected from the population $\mathbf{L}$ during each generation is used to update the particle positions $\mathbf{L}'$ through competitive learning. Non-dominated sorting and crowding distance strategies are used to select elite particles. To update each particle $\mathbf{l}_m$, two elite particles, $\mathbf{a}$ and $\mathbf{b}$, are randomly drawn from $\mathbf{E}$. They compete by comparing their angular proximity to $\mathbf{l}_m$ by computing the angles θ_1 and θ_2 between $\mathbf{a}$ and $\mathbf{l}_m$, and $\mathbf{b}$ and $\mathbf{l}_m$, respectively. The particle closest to $\mathbf{l}_m$ becomes $\mathbf{l}_w$ and it is used to update its velocity, $\mathbf{v}'_m$. Vectors $R_1, R_2 \in [0, 1]$ are randomly generated to update the particle velocities. For particle m, the updates are obtained according to Eqs. (16) and (17) for $\mathbf{v}'_m$ and $\mathbf{l}'_m$.

$$\mathbf{v}'_m = \mathbf{R}_1 \mathbf{v}_m + \mathbf{R}_2 \left(\mathbf{l}_w - \mathbf{l}_m\right) \tag{16}$$

$$\mathbf{l}'_m = \mathbf{l}_m + \mathbf{v}'_m \tag{17}$$

The updated set $\mathbf{L}'$ composed of $\mathbf{l}'_m$ is then perturbed using polynomial mutation to improve the likelihood of escaping local optima. While not shown explicitly in Fig. 1, particle velocities, $\mathbf{v}_m$, are also initialized randomly. A comprehensive description of the CMOPSO algorithm adopted in this study can be found in Zhang et al. (2018).

Table 1
Impact of topological change on system voltage and SSS (IEEE 30-bus).

#	Scenario	V_r (%)	σ_{max}	ζ_{min} (%)
1	Base	–	−0.0711	2.1266
2	Line 28 OFF	−7.08	−0.0697	2.0903
3	Line 34 OFF	−2.39	−0.0492	1.7505
4	Line 6 OFF	−1.59	−0.0678	2.0584
5	Line 30 OFF	−1.43	−0.0656	2.0838
6	Line 31 OFF	−0.98	−0.0523	1.8026
7	Line 2 OFF	−0.95	−0.0699	2.1138
8	Lines 30, 39 OFF	−4.82	−0.0649	2.0021
9	Lines 40, 32 OFF	−3.47	−0.0388	1.5395
10	Lines 6, 12 OFF	−1.59	−0.0678	2.0584

Table 2
Impact of topological change on system voltage and SSS (IEEE 39-bus).

#	Scenario	V_r (%)	σ_{max}	ζ_{min} (%)
1	Base		−0.1356	1.5762
2	Line 23 OFF	−4.11	−0.0161	1.5716
3	Line 21 OFF	−0.53	0.1188	−5.7216
4	Line 10 OFF	−0.35	−0.1056	1.5309
5	Line 11 OFF	−0.15	−0.1075	1.5601
6	Line 28 OFF	−0.07	−0.1343	1.4302
7	Lines 7, 11 OFF	−0.6	0.2166	−10.2539
8	Lines 9, 12 OFF	−0.02	0.1338	−7.2797
9	Lines 0, 29 OFF	−0.29	0.0254	−1.1315
10	Lines 18, 21 OFF	−0.29	0.1995	−10.0295

4. Results and discussion

We used a laptop computer with an Intel® $Core_{TM}$ i7-8665U process and 16 GB of RAM for the simulations. The approximate average time taken to run an iterate over 50 generations for a population size of 100 was 26 min. The algorithm includes power flow computations and small signal stability analysis (SSSA) each time the objective functions are evaluated. A significant fraction of computation time is contributed by the SSSA and power flow computations, which are done using PSAT. The stopping criterion for the algorithms was the maximum number of function evaluations which is directly related to the maximum number of generations. Tests using a large population of about 700 and different initialization points yielded the same optimal results.

4.1. Results of impact of topological reconfiguration on IAO

For each scenario, the parameters of interest were: (a) bus voltage difference (in per unit (p.u.)) before and after switching of the buses associated with the lines that are switched off; (b) lowest damping ratios; (c) largest eigenvalues and (d) presence of oscillations from the mode shapes. The results for both IEEE 30-bus and IEEE 39-bus models are shown in Tables 1 and 2 respectively and in Figs. 2–7.

4.1.1. Discussion

The results in Tables 1 and 2 show that topological change by switching off some transmission lines indeed helps in controlling voltages, since after each scenario, the voltage becomes lower than the base case (i.e. voltage regulation which is the percentage difference in voltage before and after switching becomes negative). The impact of each transmission line on the various bus voltages is different although quite significant in some scenarios, being in excess of 5%. Switching off multiple lines has the general effect of lowering bus voltages even more.

It was however observed that for every corresponding scenario, there was a consistent drop in the damping ratio, indicating a decrease in system strength/stability compared to the base case. Some scenarios under the IEEE 39-bus model exhibited even negative damping, an indication of growth in the magnitude of oscillations. It can be seen that even at base case, the damping ratios (2.1266% for IEEE 30-bus and 1.5762% for IEEE 39-bus system) were already lower (most utilities specify a minimum damping ratio of 3%–5%), but switching off the lines impacted negatively on the networks. Multiple line switching was seen to cause severe impacts (mostly resulting in negative damping ratio in IEEE 39-bus model).

The real part of the eigenvalues grows larger from negative values (in base case) tending towards positive for all the scenarios. This is an indication of small signal oscillations, which is basically IAO since the frequencies of the oscillations are less than 1.0 Hz. Some scenarios result in positive values of real part of the eigenvalues (especially in IEEE 39-bus model) which confirms small signal instability. In Fig. 2, the eigenvalue plot is presented for the base case, i.e. before any topological change, where it is seen that there are no instances of instability since all the eigenvalues are on the negative side of the S-plane. Some results of Table 2 that depict instability and small signal oscillations are further corroborated by the eigenvalue and mode shape plots presented in Figs. 3–7. The eigenvalue plots with at least one positive real part correspond to the mode shape plots where there is evident mode swinging of some generators against others at very low frequencies confirming IAO.

Results of the studies carried out in both IEEE 30-bus and IEEE 39-bus agree that topological reconfiguration can facilitate voltage regulation but compromises SSS.

Table 3
Simulation results for IEEE 30-bus and IEEE 39-bus systems using CMOPSO and NSGA-III. For each bus system and optimization algorithm, the results of prioritizing each of the objective functions is shown. CMOPSO converges to the same result for both bus systems and both algorithms converge to the same result in the IEEE 39-bus system.

Bus system	Priority	Algorithm	σ_{max}	ζ_{min} (%)	Off lines
IEEE 30-bus	σ_{max}	CMOPSO	−0.0735	2.2049	36, 37
		NSGA-III	−0.0713	2.1321	8
	ζ_{min} (%)	CMOPSO	−0.0735	2.2049	36, 37
		NSGA-III	−0.0703	2.1372	3
IEEE 39-bus	σ_{max}	CMOPSO	−0.1452	2.6595	0, 14
		NSGA-III	−0.1452	2.6595	0, 14
	ζ_{min} (%)	CMOPSO	−0.1452	2.6595	0, 14
		NSGA-III	−0.1452	2.6595	0, 14

4.2. Results of optimization of topological reconfiguration by CMOPSO and NSGA-III

Solutions for the various generations/iterations over which the algorithms were running are shown in Fig. 8(a) and (b) for CMOPSO and NSGA-III respectively for IEEE 30-bus system. Similarly, the results for IEEE 39-bus system are shown in Fig. 8(c) and (d) or CMOPSO and NSGA-III, respectively. The PlatEMO results of the optimization process are shown in Table 3 for IEEE 30-bus and IEEE 39-bus systems. Because in general the solutions of the non-dominated optimizers are Pareto optimal, variations of the solutions that give the best of each of the objective functions from the final solution set are given to facilitate comparison. Table 4 shows the IEEE 30-bus and IEEE 39-bus system results selected from the final solution sets of both algorithms to prioritize minimizing σ_{max} (Objective 1) and then maximizing ζ_{min} (Objective 2). The decision points for all the selected solutions are also given in the table.

4.2.1. Discussion

Fig. 8(a)–(d) show that the more the number of generations specified, the better the stability criteria (i.e. damping ratio and eigenvalue) the algorithm yields. The eigenvalue results presented across all the tables indicate that the optimized switching does not lead to small signal instability since the maximum eigenvalues are all in the negative range. In Table 3, it is noted that CMOPSO algorithm converges to single solution that optimizes both σ_{max} and ζ_{min} for the IEEE 30-bus bus

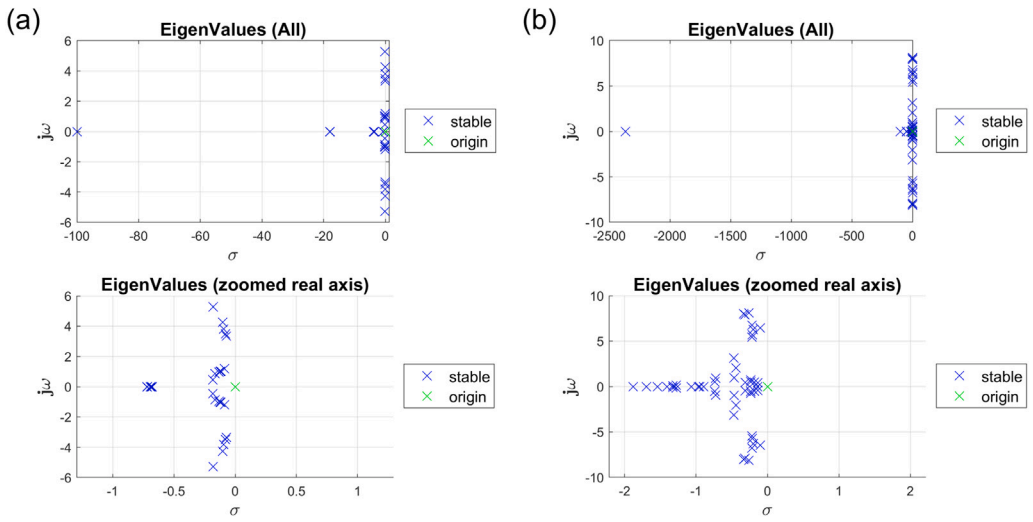

Fig. 2. IEEE 30-bus (a) and IEEE 39-bus (b) eigenvalue plot at base case (stability).

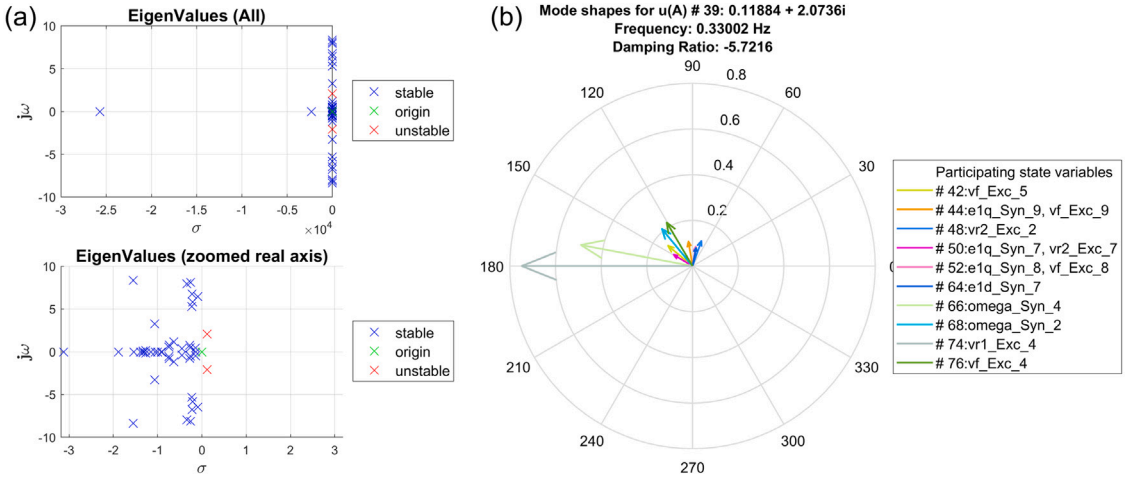

Fig. 3. IEEE 39-bus eigenvalue (a) and mode shape (b) plots when line 21 is switched OFF (instability).

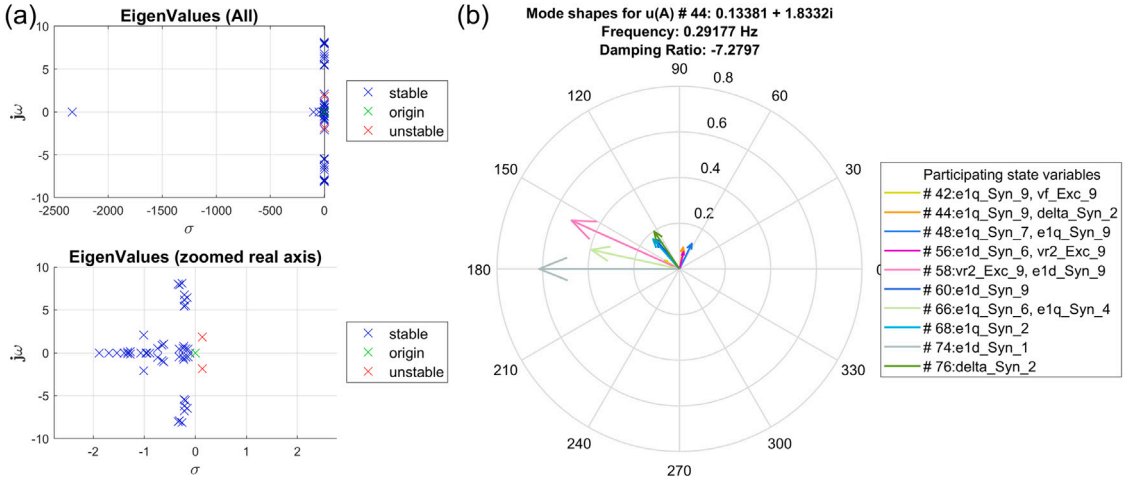

Fig. 4. IEEE 39-bus eigenvalue (a) and mode shape (b) plots when line 7 and 11 are switched OFF (instability).

model. However, NSGA-III yields slightly different results when each of the two objectives are prioritized from the final solution set. Results of both algorithms however give stable indications for SSS, although CMOPSO results are slightly superior compared to NSGA-III.

For the IEEE 39-bus model, both algorithms interestingly give the same results, which all meet the stability criteria set by the constraints. The results for both bus systems show the marginal superiority of CMOPSO over NSGA-III. The total number of lines in the IEEE 30-bus

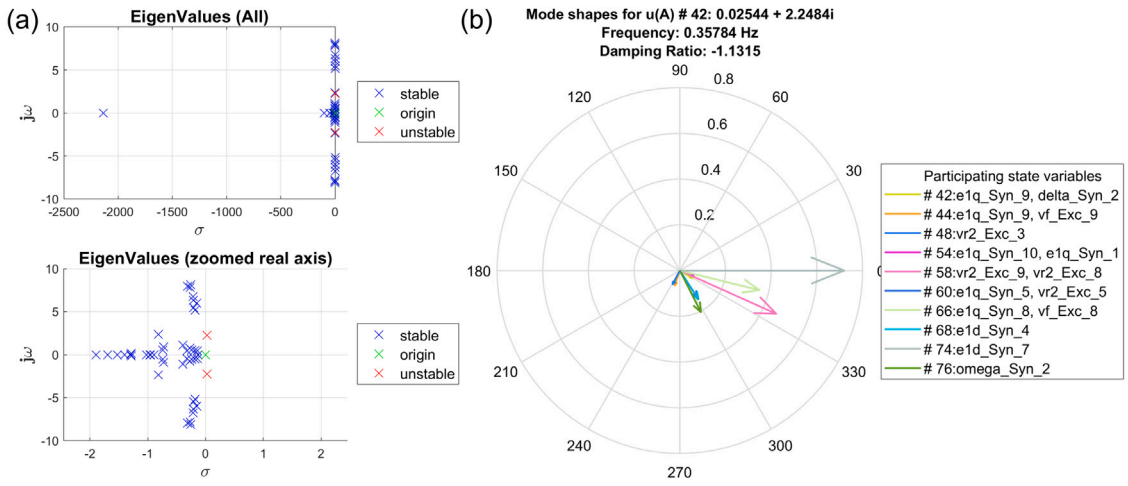

Fig. 5. IEEE 39-bus eigenvalue (a) and mode shape (b) plots when lines 9 and 12 are switched OFF (instability).

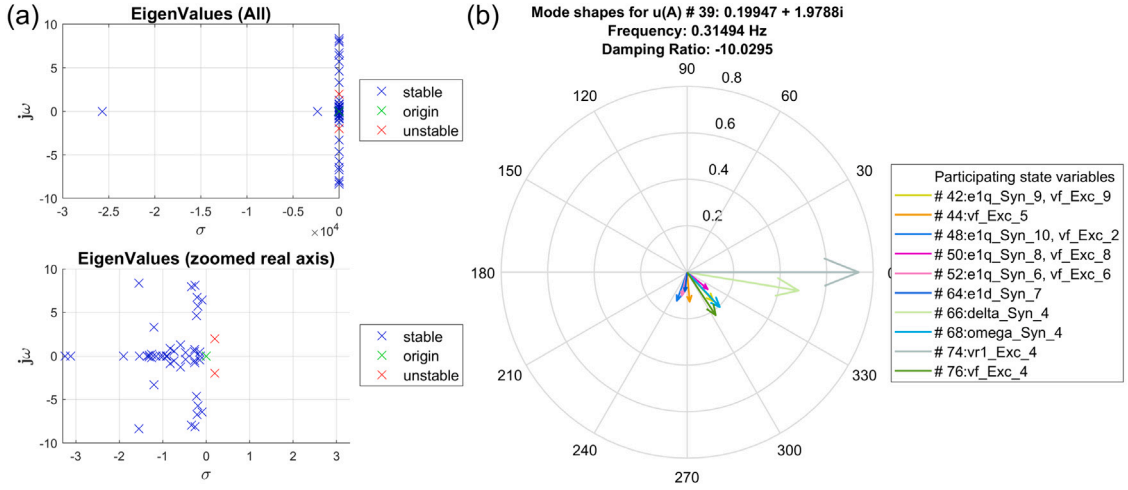

Fig. 6. IEEE 39-bus eigenvalue (a) and mode shape (b) plots when lines 0 and 29 are switched OFF (instability).

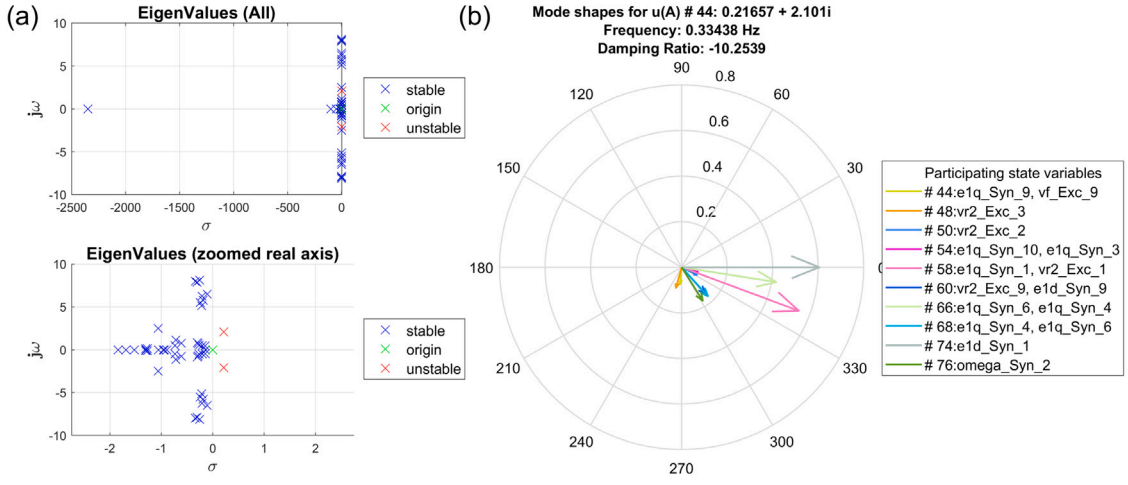

Fig. 7. IEEE 39-bus eigenvalue (a) and mode shape (b) plots when lines 18 and 21 are switched OFF (instability).

system was 41 while the total number of lines in the IEEE 39-bus system was 34. The CMOPSO algorithm therefore did a better exploration of the solution space for a system with a larger number of lines.

Since the transmission system plays a very critical role in the power system especially with the emerging complexity in power interconnections, enhanced penetration of renewable energy resources and the

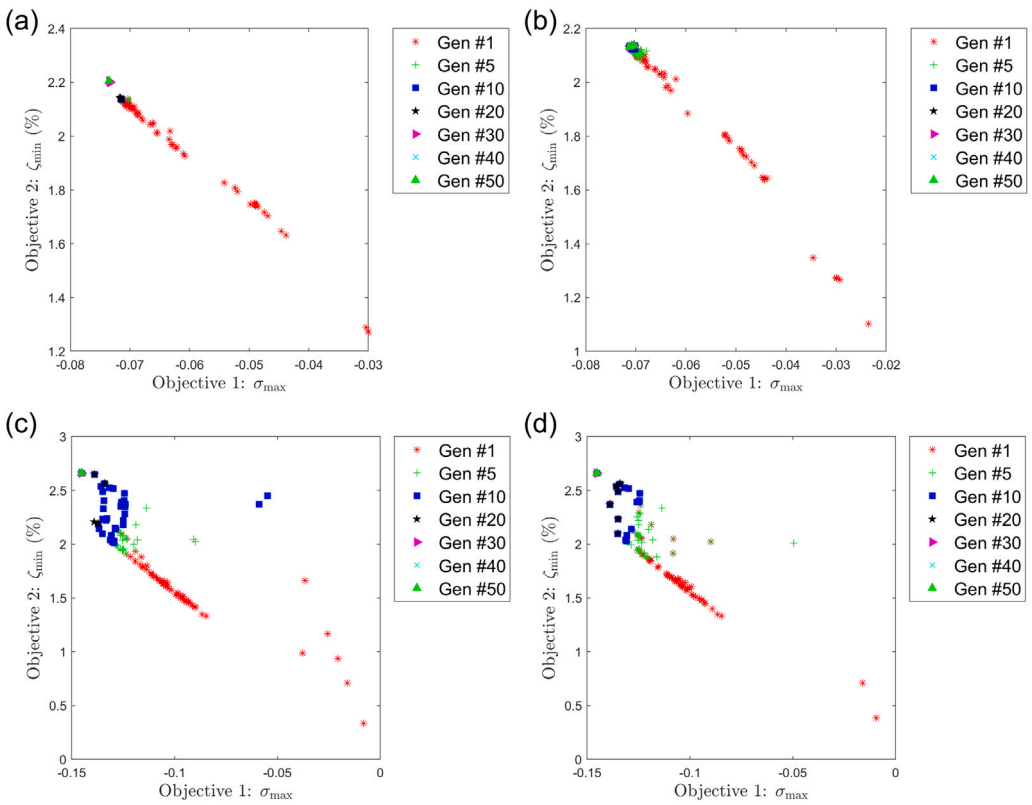

Fig. 8. Solutions in selected generations. CMOPSO (a) and NSGA-III (b) for IEEE 30-bus and CMOPSO (c) and NSGA-III (d) results for IEEE 39-bus. For all cases, there does not appear to be significant change in results after 30 generations.

increased enforcement of regulations in the power sector, the proposed algorithm was also tested on the IEEE 68-bus system which is a larger test system and provides a better representation of the real-world power system complexities. Extending this study to this bus system therefore demonstrates the scalability and robustness of the proposed method.

Table 4 presents a comparison between the results of base case and optimized switching (by CMOPSO) on IEEE 30-bus, IEEE 39-bus and IEEE 68-bus models. From the table, it can be seen that for IEEE 30-bus system, the optimized switching yields higher values of damping ratios over the base case (3.68%). The optimized switching also improves the eigenvalues above the base case (3.38%). Similarly, for the IEEE 39-bus system, the optimized switching yields higher values of damping ratios over the base case (68.73%). The optimized switching also improves the eigenvalues above the base case (7.08%). Again, for the IEEE 68-bus system, the optimized switching yields higher values of damping ratios over the base case (83.68%). The optimized switching also improves the eigenvalues above the base case (109.48%). It is also noted that the algorithm switches off two lines, namely lines 50 and 65.

The optimization algorithm caps the voltage regulation at ±10% (0.1 p.u.). While the driver for topological reconfiguration by transmission switching is the control of high voltages, it has been observed that when it is done without optimization, it has the potential of causing inadvertent lower voltages that are outside the acceptable range of voltage regulation. This can be seen in Table 1 where after switching off Line 28 in the IEEE 30-bus model, the regulation becomes −7.08% which is almost outside the acceptable criteria. It is also seen in Table 2 that voltage regulation becomes −4.11% after switching off line 23 in the IEEE 39-bus system, which is tending closer to violation of the allowable margin. The optimization algorithm therefore ensures that the voltage is constrained within acceptable limits and topological reconfiguration ensures that the system does not get into voltage instability.

Table 4
Comparison of base case and CMOPSO optimized switching parameters for IEEE 30-bus, IEEE 39-bus and IEEE 68-bus systems.

Bus system	Parameter	Base case	Optimized
IEEE 30-bus	ζ_{min} (%)	2.1266	2.2049
	σ_{max}	−0.0711	−0.0735
IEEE 39-bus	ζ_{min} (%)	1.5762	2.6595
	σ_{max}	−0.1356	−0.1452
IEEE 68-bus	ζ_{min} (%)	0.7193	1.3212
	σ_{max}	−0.0232	−0.0486

These observations are proving that the proposed optimized methodology of topological reconfiguration for voltage control actually improves SSS.

5. Conclusion and recommendation

This study has employed quadratic eigenvalue analysis to confirm that topological reconfiguration through transmission line switching can be used to control system voltages especially during high voltage regimes. It has further confirmed that topological reconfiguration when implemented without considering system stability results in IAO or in worst cases, in actual instability.

This work has therefore proposed a method which uses MOPSO to optimize implementation of topological reconfiguration during voltage control to avoid inter area oscillatory instability. The proposed method checks the whole network, and not only its particular sections. It has been tested in IEEE 30-bus, IEEE 39-bus and IEEE 68-bus system models. The results indicate that when this method is implemented, SSS is improved (considering the eigenvalues and damping ratio) alongside voltage control.

Transmission system operators (TSOs) need to be conscious that as they implement topological change by transmission line switching to control voltages, they may subject the power system to IAO, which could impair system integrity in terms of SSS. This proposed method may therefore save the operators from relying on intuition which is prone to human error as they make operational decisions during topological reconfiguration. This method is very useful during low voltage regimes which occurs after the peak hours in the evenings (as per most utility load profiles) or some weekends or even after certain dispatch procedures. For the utilities in the developing countries, the only challenge is that for its practical or real-time viability, the utility must have very accurate and validated steady-state and dynamic power system models; and install the wide area monitoring systems (WAMS) which are based on phasor measurement units (PMUs). The system control engineers have also to be trained in conducting the required simulations during operational planning.

Further research work should entail an analysis of the impact of this proposed method on the transfer capacity of the power system since it involves taking out some transmission elements out of service. This is because, to the best of our knowledge, available literature in this area does not indicate a study that considered transfer capacity as a constraint in optimization of SSS-constrained topological reconfiguration.

CRediT authorship contribution statement

Alloyce Godia Oduor: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Josiah Lange Munda:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Aloys Oriedi Akumu:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Luke Oduor Otieno:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The article processing charge (APC) for this paper is covered by Tshwane University of Technology, Pretoria 0183, South Africa.

Data availability

Data will be made available on request.

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