MINIMIZING THE IMPACT OF CONTINGENCY IN MULTIPLE-PERIOD SHORT-TERM OPERATIONAL PLANNING WITH RAS-FUBM FOR WIND INTEGRATION

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Abstract

Renewable energy-based power systems are highly influenced by weather, creating uncertainty and variability in output that fluctuates over time, making the balancing of supply and demand much more challenging. A deterministic optimisation tool has limitations associated with the security operation of short-term operational planning. To address the issue, this paper proposes a multiple period Security Constraint Optimal Power Flow (SCOPF) short-term operational planning incorporated with Remedial Action Scheme Flexible Universal Branch Model (RAS-FUBM), aiming to mitigate the contingencies in the network system. The proposed method utilises scaling factors and a partitioning technique, considering day-ahead planning with a duration of 24 hours. The effectiveness of RAS-FUBM controls (i.e., RAS-FUBM Conventional Control (CC) and RAS-FUBM Droop Control (DC)) has been demonstrated through simulation results, evaluating the overall generation costs, voltage profiles and active power flows. Both controls were able to improve two imperative variables, voltages and active power flows, achieving a stable state when the contingency struck the system. Observations indicated that RAS-FUBM DC demonstrated a lower cost. The objective of representing uncertainty with a time horizon in the SCOPF problem is to assist the Transmission System Operator (TSO) in making better decisions, leading to more economical solutions, improved security and reduced risk.

1 Introduction

The Ten Point Plan for a Green Industrial Revolution aims to establish the United Kingdom (UK) as a global leader in green energy, through achieving net zero carbon emissions by 2050. As part of this ambitious plans, the UK intends to double its offshore wind energy capacity to 40GW by 2030 [1]. This transition implies that the power system is becoming increasingly dependent on weather conditions, which operational planning is inevitably affected by uncertainty due to the variability in its output. In the past, demands and discrete events (e.g., generator or transmission line failures, equipment malfunctions, or natural disasters) were the uncertainties that Transmission System Operators (TSOs) had to account for during the planning process. Conversely, one common issue they face is making decisions amidst pervasive uncertainty in time related forecasts [2]. Managing this uncertainty in power system planning, either for the operational or real-time, is critical as it involves many considerations and analyses in order to ensure the reliability and resilience of the network system. The goal of including uncertainty in this system, is to help TSOs make optimal choices that lead to more economical solutions, improved security and lower risk [3].

Wind integration has substantial effects on the operations of the power system as it entails inherent uncertainty and variability (i.e., fluctuating throughout periods of minutes, hours, or even days) [4], which makes achieving system balancing (i.e., supply and demand) much more challenging. In contrast to fossil fuels, wind power cannot be directly regulated since wind farms lack the ability to increase their production upon request; they can only decrease the output. An effective approach to define and manage wind uncertainty is therefore necessary for stable and safe operation of the power system, and accurate wind power forecasting is essential to planning of the power system operation [5]. There has been much discussion on the quality of wind forecasts. Researchers in [6] investigated the uncertainty of wind power using stochastic AC Optimal Power Flow (ACOPF), based on wind power forecasting scenarios over multiple periods (i.e., 24 hours). A robust optimization model for the multi-period ACOPF has been developed in [7]. The analysis of published literature indicates a focus on expanding the multi-period ACOPF to incorporate uncertainty in wind energy. However, these studies overlook the consideration of contingency scenarios (i.e., outages of components such as transmission lines or generators), which are essential for maintaining the security criterion in power system.

The security criterion refers to a set of standards, guidelines and measures that must be adhered to by TSOs to implement appropriate actions and mitigate the risk of cascading events (e.g., blackout) in the power system. One common rule that typically applies in the criterion power system is N-1, which specifies that the system should continue to operate following the loss of any one component (e.g., transmission line, generator, transformer, etc.) without compromising system operation [8]. The researcher in [9] addressed the gap in contingency studies for the stochastic ACOPF with N-1 security, by introducing the concept of stochastic multi-period AC Security Constrained (SC) OPF. This study incorporated a weight factor (e.g., temperature) and slack variable into the standard SCOPF formulation to minimise the overall system risk. In order to maintain stability and secure the system from cascading events (i.e., partial or total blackouts), Remedial Actions Scheme (RAS) (i.e., automatic protection of network system required upon the detection of contingencies) was develop as part of power system design, control and operation based on the results of security assessment [10]. Extensive research has been conducted on RAS in the AC transmission system, encompassing both online and offline assessments. One notable research by [11] focused on High Voltage Direct Current (HVDC)-RAS for online operation, adapting an event-based approach for meshed Voltage Source Converter (VSC)-HVDC systems. However, there remains a research gap in incorporating RAS with HVDC, particularly in the context of Multi-Terminal HVDC (MT-HVDC) systems.

Partitioning concepts are used in the power system to simplify the analysis of system operation and management by breaking it down into smaller, manageable subsystems or zones. This concept can be classified into several types such as Geographic Partitioning (GP), operational partitioning, hierarchical partitioning, etc [12]. Significance of this technique in steady-state analysis was underlined by [13], especially for transmission congestion analysis related to power resources allocation, determining zones prices [14] and decomposing the system into multiple areas [15]. Implementing this mechanism can help TSOs expedite the decentralization process and reform power system development plans [16]. In this paper, the partition method is used to divide the network system into two zones utilising the GP technique to differentiate between demand and wind power generation.

The paper is structured as follow: Section 2 introduces the operational planning, which presents the proposed methods of multi-period planning using the scaling factor and network partitioning. Additionally, this section explores the RAS-FUBM scheme with SCOPF to enhance power system security and stability during the contingencies. In section 3, a comprehensive analysis of the result is presented, encompassing four scenario events with implementation of RAS-FUBM controls. Finally, section 4 concludes the paper.

2. Operational Planning in the Power System

Operational planning and real-time operation form the framework for short-term decision making in power systems, within a time- horizon varying from minutes/hours, days/weeks to month/years. The real-time operation involves a series of decisions (e.g., demand response, scheduled generation, etc), which are planned in a sequentially and highly predictable manner (i.e., the outcome of power system activities can be reliably projected and accurately anticipated thorough planning conducted beforehand) [17]. Meanwhile, the operational planning studies serves as an initial stage of decision planning before real-time operation. This stage is vital for maintaining a reliable and secure network, while identifying operating bounds that meet all reliability criteria. The criteria adhere to all technical, environmental and contractual constraints [18]. Initially, the primary objective of this planning was to minimise costs by aligning with the load duration curve (i.e., graphical representation illustrating the relationship between the electricity demand (i.e., load) and the duration for which that demand occurs). However, planning problems are becoming more challenging due to the increasing penetration of renewable generation sources (e.g., wind and solar), which introduce additional operational constraints subject to variability and uncertainty. Therefore, accurate planning considering grid congestions (i.e., grid bottlenecks) and other constraints (e.g., operation and component limits) becomes highly important [19].

Operational planning in the power system is categorised into long-term, medium-term and short-term, with studies influenced by the respective time horizon. Each planning has a different timeline with long-term reaching more than three years, medium-term ranging from one month up to two years and short-term spanning days to weeks [20]. Planning in the long-term includes generation and transmission expansion planning, policy development and investment decisions [21], whilst short-term planning addresses problems such as economic dispatch, power flow, optimal power flow, etc (refer to Figure 1) for a visual representation pertaining to each operational planning).

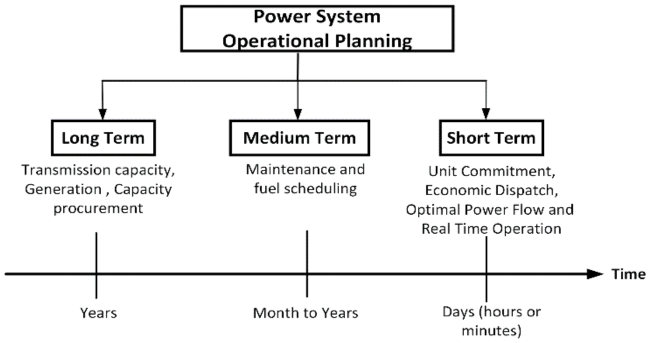


Figure 1: Operational Planning in the Power System.

2.1 Short-Term Multi-Period Operational Planning

In the context of steady state analysis, the Economic Dispatch (ED) problem is viewed as a straightforward single period problem, which aims to find the optimal generator dispatch points that satisfy a specified demand while minimising the total cost [22]. Nevertheless, the fundamental design of power systems aims to accurately predict the pattern of hourly electricity demand and wind power forecasts. This forecast is crucial as demand behaviour is influenced by various factors: a) hour of the day; b) day of the week; c) weather conditions; d) strikes or other political events; e) demand response strategies; f) pricing strategies; and g) other economic conditions [23]. Wind forecasts are constantly influenced by weather conditions and are intermittent as well as fluctuating throughout time spans. In [24], authors emphasized the significance of wind resources assessment for wind farm projects and its impact on power systems. The multi-period ACOPF problem has also been studied by [25], which underlined that in terms of cost effectiveness and managed uncertainty in power demands, a robust ACOPF with multi-period approach offers greater advantages over a deterministic ACOPF single period model.

This paper introduces an extension of deterministic operational planning, which was originally a single period problem, to encompass multiple periods by incorporating the developed scaling factor. The hourly power system operation for loads and winds are generated using appropriate scale factors, to incorporate the inherent variability of both demand and wind generation. In this way, a multi-scenario multi-period ACOPF is developed in this paper for purposes of short-term planning of systems, with high wind integration. This will be further elaborated in the next section. The research focuses on the short-term operational planning, as this roadmap is vital for the TSO to manage day-to-day operation of the grid, respond to changing conditions, and maintain a balance between demands and wind sources while adhering to operational constraints.

2.1.1 Scaling Factors for Demand and Wind

In a single period deterministic OPF, the demands modelled are constant and represented as a specified quantity of real and reactive power consumed at a particular bus. These standard demands are formulated as follows:

$$S_d^i = P_d^i + jQ_d^i = D_d^i \quad (1)$$

With "i" is the bus index, S is the complex power (MVA), P is the demand active power (MW), and Q is the demand reactive power (MVAR). The matrix size representing complex demands at all buses is N_b x 1, which N_b refers to the number of buses.

A standard generator is represented by a complex power injection at a specific bus, and the formulation for this power at generator"k" is as below:

$$S_g^k = P_g^k + jQ_g^k = W_g^k \quad (2)$$

Where S is the complex power (MVA), P is the generator active power (MW), and Q is the generator reactive power (MVAR). The size of the matrix representing all generators is N_g x 1, where N_g is the number of generators [26].

In a single period problem, the vectors D_d^i and W_g^k in equations (1) and (2) can be represented in the following form:

$$D_d = [d_1 \quad d_2 \quad d_3 \cdots\cdots d_i]^{\mathrm{T}}_{N_b \,\mathrm{x}\, 1} \quad (3)$$

$$W_w = [w_1 \quad w_2 \quad w_3 \cdots\cdots w_k]^{\mathrm{T}}_{N_w \,\mathrm{x}\, 1} \quad (4)$$

Where N_b and N_w are numbers of bus and wind generator, respectively. In order to extend this formulation to multiple periods, scale factors (α) sampled from a uniform (u) distribution (i.e., $\alpha \sim u(0,1)$) can be defined for every time period $t \in [1, \ldots, N_t]$. This will yield a 1 x N_t row vectors as seen in (5). The scale factors for wind and demand in the vector form can be expressed as shown below:

$$\alpha = [\alpha_1 \quad \alpha_2 \quad \alpha_3 \cdots\cdots \alpha_t]_{1\,\mathrm{x}\,N_t} \quad (5)$$

From equations (3), (4) and (5) the demand and wind models for the multiple period scenarios at time "t" at bus "j" and wind "k" are represented by matrices S_d^t and S_w^t :

$$S_d^t = D_j \alpha_d^{\mathrm{T}} \quad (6)$$

$$S_w^t = W_k \alpha_w^{\mathrm{T}} \quad (7)$$

The matrix size for multiple period scenario is N_t x N_b for the buses and N_t x N_w for the winds represented in the form shown below:

$$S_d^t = \begin{bmatrix} \alpha_1 d_1 & \alpha_2 d_1 & \cdots & \cdots & \alpha_t d_1 \\ \alpha_1 d_2 & \alpha_2 d_2 & \cdots & \cdots & \alpha_t d_2 \\ \alpha_1 d_3 & \alpha_2 d_3 & \cdots & \cdots & \alpha_t d_3 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \alpha_1 d_j & \alpha_2 d_j & \cdots & \cdots & \alpha_t d_j \end{bmatrix} \quad (8)$$

$$S_w^t = \begin{bmatrix} \alpha_1 w_1 & \alpha_2 w_1 & \cdots & \cdots & \alpha_t w_1 \\ \alpha_1 w_2 & \alpha_2 w_2 & \cdots & \cdots & \alpha_t w_2 \\ \alpha_1 w_3 & \alpha_2 w_3 & \cdots & \cdots & \alpha_t w_3 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \alpha_1 w_k & \alpha_2 w_k & \cdots & \cdots & \alpha_t w_k \end{bmatrix} \quad (9)$$

In this paper, a scaling factor is proposed to modify standard demands or winds, enabling variability in both profiles across different time periods. This factor can be higher or lower depending on its application to the network analysis, resulting in either an increase or decrease in demands or winds compared to the basecase loads or wind powers. Figure 2 illustrates the scaling factor for 12 hours at two buses, in comparison to the basecase.

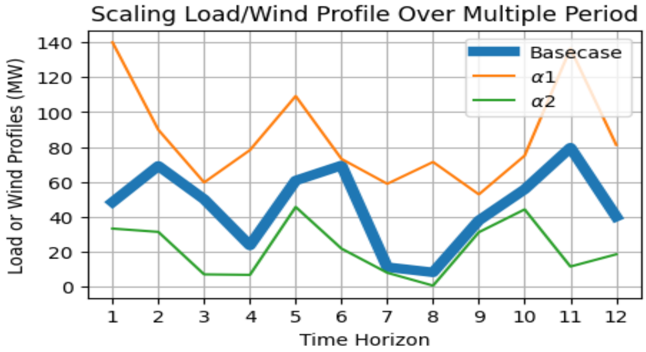


Figure 2: Scaling factor at two buses.

2.1.3 Partitioning Technique

In load flow analysis, wind generators are represented in the power system as negative loads. These generators are represented as PQ buses, where the reactive power generation depends on the terminal voltage of the generator, resulting in an inability to regulate the bus voltage [27]. This poses a challenge for the TSOs as they must independently differentiate between demand and generation. Furthermore, forecasting for wind and load becomes challenging as both elements are categorised under the same type of buses. To address these problems, this paper introduces GP method that partitions the system into multiple load zones. These zones are represented using an N_b-element vector, where each element corresponds to specific load or wind elements in the system. The values in the vector indicate the load zone assignment for each bus. If the value is 0, it means that the loads at that particular bus will not be modified. This can be defined as follows:

$$Load\ zone(1{:}b) = p, \quad p = 1,2, \ldots\ldots N_b$$
$$Load\ zone(1{:}w) = s, \quad s = 1,2, \ldots\ldots N_w$$
$$Load\ zone(1{:}b) = 0,$$

Where "b" and "w" are nodes bus and wind. In this paper the entire grid is divided into two zones and each region is identified with two different line colours (refer to Figure 5). Partition 1 is designated for demand, whilst wind energy production is allocated in partition 2. This technique enables the analysis of uncertainty by incorporating scaling factors (as discussed in the previous section) for renewable generation resources and demand forecasts.

2.2 Remedial Action Scheme Flexible Universal Branch Model Scheme

The RAS-FUBM scheme presented in this paper is an improved optimisation model for modelling two types of control strategies, afforded by the VSCs in a MT-HVDC setting, namely conventional control and droop control, which has been studied by [28].

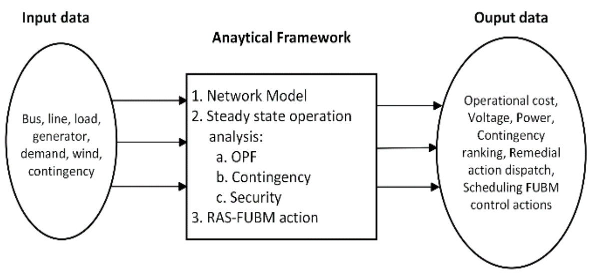


Figure 3: RAS-FUBM Framework

This scheme integrated control features from the "VSC in model" of the Flexible Universal Branch Model (FUBM), developed in [29]. It was designed: a) to alleviate the congestion in transmission lines; b) to reduce the security risk posed by wind power uncertainty; and c) to enhance the security and stability of the system embedded with the MT-HVDC system. Figure 3 illustrated an analytical framework for the RAS-FUBM that begins with input data such as buses, generators, lines and other relevant components in the power system. The detailed outline of this framework can be seen as Figure 4.

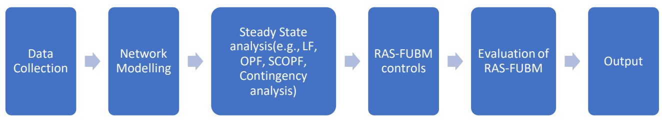


Figure 4: Detailed Outline of the RAS-FUBM Framework.

In the data collection step, all the necessary input data (e.g., buses, generators, lines, demand consumption, contingency, wind, etc) is gathered for the power system model. These data may come from the historical records, measurements or simulation studies. Second step is to develop network modelling that captures connectivity and physical characteristics of the system. The purpose of this step is to simulate and analyse the behaviour of the power system including power flows, voltage profile and system stability across the system. Some key points that need to be considered are as follows :a) network elements (i.e., characteristics and parameters of each components); b) topology (i.e., connection points and paths for power flow within the system); c) impedance and admittance; d) bus representation (i.e., generator, load or slack bus); and e) power flow equations (e.g., Kirchhoff's laws, Ohm's law, Newton Raphson, etc). Steady state analysis is the third step that involves running the simulations based on scenarios (e.g., basecase, contingency, or multiple period), analysing results, making necessary adjustments and repeating the process again to achieve desired outcome. Normally, the simulations are performed using specialised tools such as Matpower and PSS/E, PSCAD, which solve the mathematical equations determining the system behaviour. At this stage, the system will be assessed on critical parameters such as voltage and power flows to identify potential issues.
The next stage is the RAS-FUBM controls that can detect critical system conditions and trigger appropriate actions. This procedure is based on the system state estimation techniques, which identify potential actions that can help mitigate the effects of contingencies. Next step is evaluation of the RAS-FUBM performance that measures how well the RAS-FUBM meets the defined performance objective during different contingencies. Final step is to produce a satisfactory output that ensures the power system continues to meet its performance objectives, whilst operating in a secure and reliable manner.

2.2.1 Security Constraint Multi-Period Optimal Power Flow

The objective function (equation 10) of SCOPF is to minimize the overall cost of electricity generation, by: a) satisfying a set of equality constraints (i.e., balancing supply and demand) (equation 11); b) inequality constraints related to operational security limits (e.g., power flows in the transmission lines) (equation 12); c) physical equipment limits (e.g., generators powers, transformers ratios, etc.) (equation 13); and d) coupling constraints (equation 14). The following statement, also known as a conventional SCOPF formulation (i.e., single period) can be represented using mathematical notation as presented below:

$$\min_{x_0, u_0 \ldots\ldots x_c, u_c} f(x_0 u_0) \tag{10}$$

s.t

$$g_{n,c}(x_c u_c) = S^{g}_{(n,c)} - S^{d}_{(n,c)} + S^{bus}_{(n,c)}, \quad n \in N, c \in C \tag{11}$$

$$h_{n,c}(x_c u_c) \leq S^{max}_{(n,m),c}, \quad (n,m) \in L, c \in C \tag{12}$$

$$x_{\min\,(n,g)} \leq x \leq x_{max(n,g)} \quad n \in N, g \in G \tag{13}$$

$$|u_c - u_0| \leq \Delta u_c \quad c \in C \tag{14}$$

Where N, C, L, G are the set of buses, contingencies, transmission lines and generators, respectively. The quadratic function "f" is the fuel cost of generating per unit active power (P^g) in the monetary units (e.g., $) as described below:

$$f = \sum_{g=1}^{Ng} a + bP^g + c(P^g)^2 \tag{15}$$

Where a, b and c are the cost coefficients that measured in units of $, $/MW and ($/MW)^2 respectively. The state and control variables represented by x_o (basecase scenarios), x_c (contingency scenarios), u_o (basecase scenarios), and u_c (contingency scenarios) consist of the following: a) $N_b\,x1$ vectors of voltage angles (θ) and magnitudes (VM); and b) $N_g\,x1$ vectors of generator active (P^g) and reactive (Q^g) power injections, which can be specified in the following form:

$$(x, u) = (\theta \quad VM \quad P^g \quad Q^g)^{\mathsf{T}}$$

"$g_{n,c}$" is the vector of equality constraints pertaining to the network's nodal power balance during steady-state operation. This vector must be equal to the difference between the complex power injections $\left(S^{g}_{(n,c)}\right)$ and the sum of complex power demands $\left(S^{d}_{(n,c)}\right)$ and net complex power injections $\left(S^{bus}_{(n,c)}\right)$ at bus n for each contingency case (c). The notation $n \in N$ and $c \in C$ indicates that the constraints hold for all possible combinations of buses, where n belongs to the set of buses N, and all possible contingencies c belong to the set of contingency cases C. This complex power is represented by a set of nonlinear active (P) and reactive (Q) power balance equations.

$$g_P = P^g_{(n,c)} - P^d_{(n,c)} + P^{bus}_{(n,c)} = 0 \quad (16)$$

$$g_Q = Q^g_{(n,c)} - Q^d_{(n,c)} + Q^{bus}_{(n,c)} = 0 \quad (17)$$

The vector inequality constraints denoted by "$h_{n,c}$" pertain to operational limits on the transmission lines. The vector consists of N_L (i.e., transmission line index) branch flow limits that restrict the power flow between buses to prevent overloading or violating transmission limits. The symbol $(n,m) \in L$ indicates that the bus pair consisting of n and m is the set of transmission lines denoted by L.

The variable limits, $x_{\min(n,g)}$ and $x_{\max(n,g)}$, pertain to the constraint on the upper and lower limits of components such as VM, P^g and Q^g.

$$VM_{\min(n,g)} \leq VM \leq VM_{max(n,g)} \quad (18)$$

$$P^g_{min(n,g)} \leq P^g \leq P^g_{max(n,g)} \quad (19)$$

$$Q^g_{min(n,g)} \leq Q^g \leq Q^g_{max(n,g)} \quad (20)$$

The notation $g \in G$ indicates that the variable limits apply to all generators g within the subset of generators represented by G. The coupling constraints (equation 14) are representing the maximum allowed variations in control between pre- and post-contingency [30].

A comprehensive SCOPF problem should incorporate the time-dependent availability of emergent flexibility resources, in order to effectively manage the unpredictability of wind resources [31]. Furthermore, conducting SCOPF using time-based simulation is essential due to the dynamic nature of the system, with variables like load and renewable energy constantly changing. These fluctuations can significantly influence the system's performance (e.g., objective functions, voltages, and power flows). The expansion of the conventional SCOPF has been carried out to accommodate these requirements, whilst also incorporating RAS-FUBM actions. The new SCOPF problem has been defined as per follows:

$$\min_{\substack{x_{0t},u_{0t}\ldots\ldots \\ x_{ct},u_{ct}\ldots\ldots \\ x_{rt},u_{rt}}} f(x_{0t}u_{0t}) \quad (21)$$

s.t

$$g_{n,c,r,t}(x_{c,r,t}u_{cc,r,t}) = S^g_{(n,c,r,t)} - S^d_{(n,c,r,t)} + S^{bus}_{(n,c,r,t)}, \quad (22)$$

$$n \in N, c \in C, r \in R, t \in T$$

$$h_{n,c,r,t}(x_{c,r,t}u_{c,r,t}) \leq S^{max}_{(n,m),c,r,t} \quad (22)$$

$$(n,m) \in L, c \in C, r \in R, t \in T$$

$$x_{\min(n,g)} \leq x \leq x_{max(n,g)} \quad n \in N, g \in G \quad (23)$$

$$|u_{ct} - u_{0t}| \leq \Delta u_c \quad c \in C \quad (24)$$

$$|u_{rt} - u_{ct}| \leq \Delta u_{rt} \quad r \in R, t \in T \quad (25)$$

The variable "t" indicates the time periods, whilst x_{rt} and u_{rt} represent the state and control variables for the RAS-FUBM control strategy actions, which are in the form of:

$$(x_{rt}, u_{rt}) = (P^g \quad Q^g \quad VM \quad \theta \quad B_{eq} \quad \theta_{sh} \quad m_a \quad G_{sw})^{\mathrm{T}}$$

The variables B_{eq}, θ_{sh}, m_a and G_{sw} refer to the following: susceptance, shift angle of the VSC, tap changer ratio for the Controlled Tap-Changing Transformers (CTT) and VSC switching losses, respectively. The variable θ is the voltage angle refers to the phase angle of the nodal voltages at different buses. On the other hand, θ_{sh} denotes the phase angle of the VSC, which functions similarly to the phase angle of the Phase Shifter Transformer (PST) in controlling the active power flow between two nodes to maintain the quality of the power supply. In this research, both variables are expressed in degrees.

The coupling constraint in equation (25), which is included in the multiple period SCOPF formulation, establishes the maximum allowable action controls in the RAS-FUBM following post-contingency states. These controls actions refer to the corrective measures that need to be implemented during contingency scenarios to ensure the network system always remains secure and reliable.

3 Simulations Results

A modified version of IEEE30-bus system is used to analyse the performance of the proposed methods, which are scaling factor and partitioning technique. As discussed in *Section 2.1.3*, the network model was divided into two areas, featuring three wind farms in partition 2 and HVAC system in partition 1 (as depicted in Figure 5). The simulations are performed in Matlab on a laptop equipped with an Intel(R) Core (TM) i5-10210U CPU running at 1.60GHz (2.11 GHz), a 64-bit processor and 8.00 GB of RAM. All cases are solved using Matpower and this platform provides access to the standard data IEEE30 bus-system. Parameters related to the MT-HVDC system (i.e, converters and DC grids) can be found in [28], whilst Table 1 provides detailed control settings for the VSCs for the basecase and two types of control, which are conventional and droop controls.

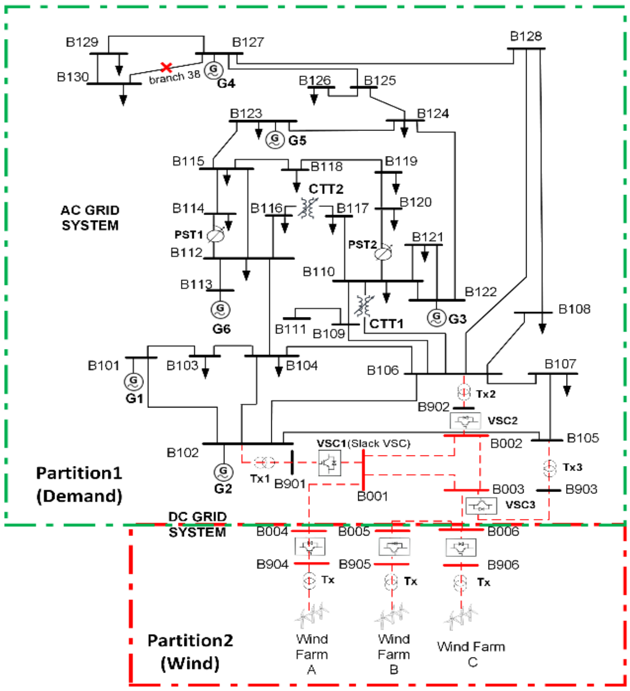


Figure 5: MT-HVDC 30-Bus System

There are three case studies conducted in this research: a) basecase; b) conventional control (i.e., DC voltage control and active power control); and c) droop control. For all cases, VSC1 is designated as the "slack VSC" (i.e., reference VSC), whilst the remaining VSCs operated based on their respective control types. In cases (a) and (b), both VSC2 and VSC3 are subjected to active power control. In case (c), VSC2 is assigned for active power control, whilst VSC3 is allocated for reactive power control. The cases also considered a contingency that adhered to the N-1 rule (i.e., outages at branch 15) with fixed probability. The probability scenario is

10% without creating the islands. This scenario is included in these simulations due to its crucial role in analysing the steady-state security of the network system. As emphasised by [32], the probability approach is essential as it enables a more reliable estimation of the system's risk.

Table 1: VSC Setting Control.

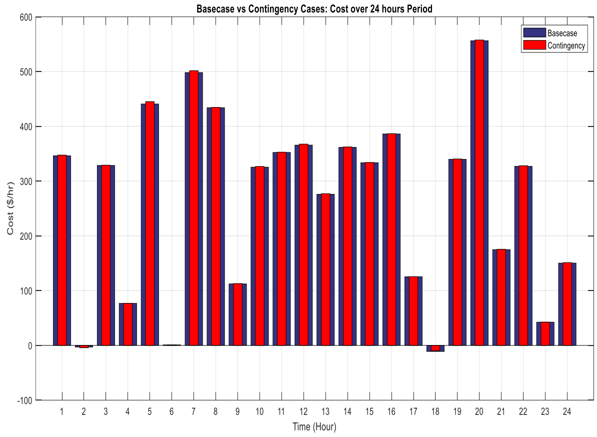
Scenario	Converter	Type	Mode	Control Constraint
Basecase	VSC1	II	4	V_f = 1.0 p.u
	VSC2	I	3	P_f = 25MW
	VSC3	I	3	P_f =15MW
Type of Control				
Conventional Control				
a. DC Voltage	VSC1	II	4	V_f = 0.98p.u
a. Active Power	VSC2	I	3	P_f = 27.5MW
	VSC3	I	3	P_f =12MW
Droop Control	VSC1	II	7	V_f = 0.98p.u P_f = 27.5MW k_{dp} = -0.1
	VSC2	I	3	P_f =12MW
	VSC3	I	2	Q_t=-25MVAR

3.1 Analysing the Result

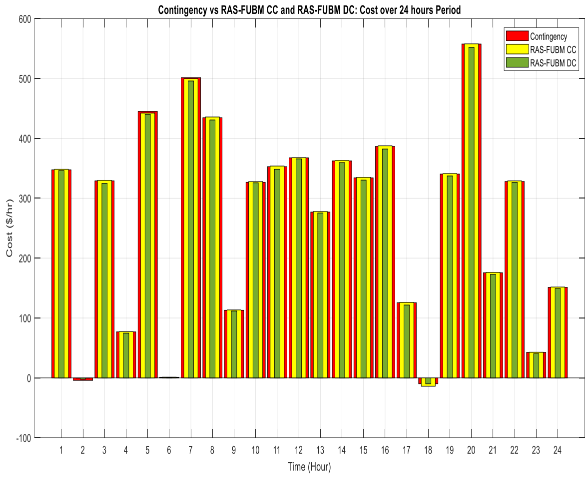
All cases successfully converged within a duration of 1344.55 seconds. Notably, the modelling with conventional control exhibits faster result times compared to droop control, with respective durations of 15.63 and 37.24 seconds.

Equation (21) provides the objective function (i.e., cost) that calculates the total cost of generation for multiple periods across each case. Figure 6 illustrates these costs, highlighting increasing costs (refer to Figure 6(a)) when contingency (i.e., branch 15 disconnected) occurs in the system throughout the entire 24-hours duration. In order to mitigate this contingency, the coupling constraint (equation 25) is introduced in the SCOPF, which corresponds to the actions taken in the RAS-FUBM controls. It is evident that the actions of the VSC with RAS-FUBM CC are more expensive and they remain the same during specific periods (i.e., t = 4, 17 and 23), as shown in Figure 6 (b). Conversely, the operational costs with the RAS-FUBM DC exhibit the lowest cost compared to all cases for the entire duration (refer to the same Figure 6). This discrepancy arises from the fact that the RAS-FUBM CC injects the maximum available power to maintain voltage stability in all buses, whilst RAS-FUBM DC distributes power among buses based on the droop gain (i.e., k_{dp}) [33]. Therefore, RAS-FUBM CC is a precise control method with higher costs, whilst RAS-FUBM DC is a stable control approach that is more cost- effective.

Figure 7 displays the voltage profile (i.e., Voltage Magnitude (VM)) of all buses over a 24-hour period for all cases. During the basecase, the VMs are consistent within the predefined lower and upper limits (i.e., 0.95p.u and 1.1p.u) as indicated in Figure 7(a). However, when an outage occurs at branch 15, resulting in a significant voltage drop below the threshold of 0.95, especially at t = 2 and t=5 (refer to Figure 7 (b)). These occurrences identified as voltage limit violations. If this continues to happen, the system may become unstable and insecure, potentially leading to cascading events such as a blackout. In order to prevent these situations, the RAS-FUBM actions (i.e., RAS-FUBM CC and RAS-FUBM DC) have been activated, resulting in voltage increases that indicated the achievement of steady-state voltage stability in the system.



(a)



(b)

Figure 6: Cost for all cases in a 24-hour period.

The active power flow (i.e., PF) from lines 25 to 35 for all cases is analysed, as shown in Figure 8. During the contingency, the system experiences more stress than the basecase, due to congested transmission lines caused by higher thermal limits on active power flow (refer to the Figure 8(a)). Therefore, to optimally alleviate this congestion, the RAS-FUBM is implemented. It is apparent that the generators (i.e., traditional and wind) can proportionally redistribute all of the active power in the contingency case when both controls (i.e., RAS-FUBM CC and RAS-FUBM DC) activated, as shows in Figure 8(b) and Figure 8(c) . PFs are vital variables in the power system as they ensure the reliability and efficiency of the system. Therefore, accurate management and control of PFs is crucial as it can: a) balance generations and demands; b) stabilise voltage levels; c) enhance power qualities; d) reduce costs; e) minimise losses; and f) ensure proper equipment functioning.

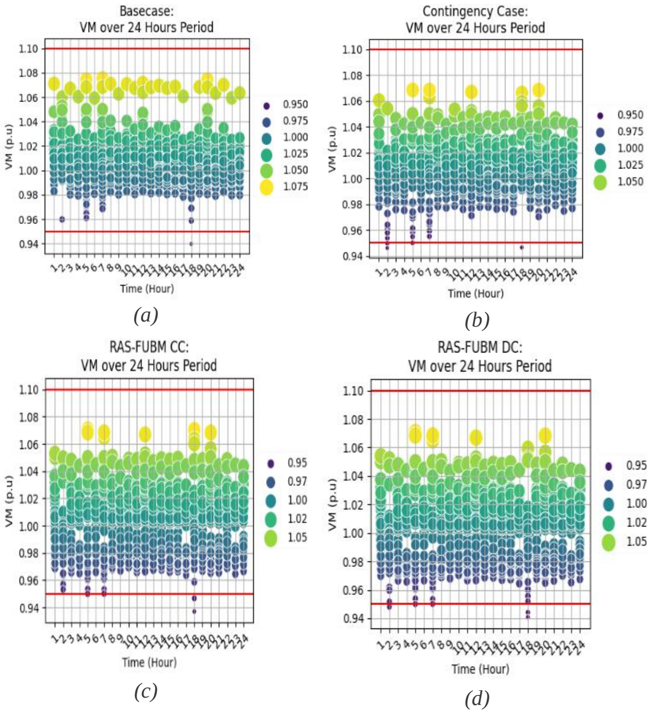


Figure 7: Voltage Magnitude for all cases across 24 Hours Period.

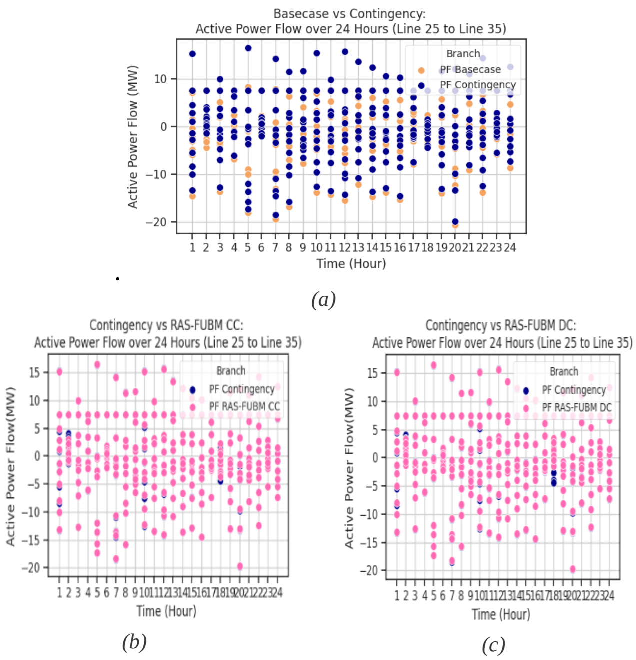


Figure 8: Active Power Flow (PF) during a 24-Hour Period.

4 Conclusion

This paper proposes a multiple-period short term operational planning incorporated with RAS-FUBM, aiming to mitigate the contingencies in the network system. The proposed method utilises scaling factor and partition technique, considering a day-ahead planning with a duration of 24-hours. It has also extended the state-of the art SCOPF formulation, by incorporating time dependency to effectively manage the unpredictability and uncertainty of wind resources and demands. The effectiveness of RAS-FUBM controls (i.e., RAS-FUBM CC and RAS-FUBM DC) has been demonstrated through simulation results, evaluating the overall generation cost, voltage profile and PF. The cost comparison shows that RAS-FUBM CC, with precise control, is more expensive compared to the RAS-FUBM DC, which offers a more economical and stable approach. These controls can restore voltage stability levels to an acceptable limit, which was unstable during contingency case. Furthermore, these controls have increased the transmission capability limits of the PF. Both controls are apparently able to redistribute PFs in a more efficient manner. The PFs are imperative variables as they ensure the reliability and efficiency of the network system. Accurate management and control of PFs are crucial not only to balance generations and demands, but also to contribute to cost reduction, particularly in the case of RAS-FUBM DC. These controls offer the benefits of ensuring the power system can be restored to a secure state after a contingency and achieving a stable operational state.

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