Probabilistic Assessment of Voltage Stability in Composite Generation and Transmission Systems

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Abstract—**Several papers have recognized the effect of uncertainties in system parameters on voltage stability analysis through probabilistic methods. In these papers, the unstable states are identified by the unsolvability of the power flow equations or the violation in the Voltage Stability Margin (VSM) minimum limit. However, voltage stability problems may also be associated with the loss of voltage controllability, when a voltage control action has the effect contrary to the expected and usual one. The main aim of this paper is to include unstable states caused by unsolvability and voltage controllability loss in the Voltage Stability Probabilistic Assessment (VSPA). The proposed method to include these two mechanisms in the VSPA is based on the combination of three techniques: the Monte Carlo Simulation Method (MCSM), the nonlinear Optimal Power Flow (OPF) and the D' Matrix Method (DMM), for the voltage stability assessment. The results demonstrate that the voltage controllability loss is an important mechanism in VSPA.**

Keywords- Composite Systems, Interior Point Method, Monte Carlo Simulation, Optimal Power Flow, Probabilistic Methods, Sensitivity Analysis, Voltage Stability.

I. INTRODUCTION

Currently, electric power systems are operating near to their limits. This operational condition has been caused by the following factors: natural growth of electric energy demand and postponement of the transmission expansion caused by routing constraints and reductions in the electricity sector budget due to economic difficulties. The operation of heavily loaded transmission lines has given rise to voltage stability problems in the electricity networks. Voltage stability is defined as the ability of a power system to maintain steady voltages at all buses after disturbances such as: load fluctuations and contingencies in the system components [1], [2]. The voltage instability states are mainly associated with two mechanisms:

i) Unsolvability of the power flow equations [3], [4]: after the occurrence of a system disturbance, the power flow equations do not have real solutions due to the violation of the maximum power transfer for the system loads. The distance between the current loading point and the maximum loading point is named as Voltage Stability Margin (VSM).

ii) Voltage Controllability Loss [1], [5]: after a disturbance, the control actions, used to correct the voltage profile, have the opposite effect to the expected one. For example, bus voltage reduction after a capacitor bank is switched on. This effect is due to the negative value of the QV sensitivity in the bus where the capacitor was switched on.

The presence of voltage instability mechanisms in a system state can be identified through the combination of the following techniques:
i) DMM [5] or Modal Analysis [6] to detect controllability loss problems;
ii) OPF [4] or Continuation Power Flow [7] to assess the solvability of the power flow equations.

This identification can be carried because the voltage instability mechanisms are based on the existence of real solutions for the power flow equations and on the sensitivity relationships between control and state variables. However, it is not possible to predict the system operational state. It is due to the stochastic behavior of load fluctuations and equipment availability. Consequently, the system is subject to an uncertainty associated with the occurrence of voltage instability states. Therefore, it is important that the voltage stability analysis should also consider the uncertainties related to random nature of system disturbances. The more appropriate techniques for modeling uncertainties associated with system disturbances in voltage stability are the probabilistic methods. The main advantages of the probabilistic methods are their ability to combine severity and likelihood to truly express the system risk [8], [9]. Furthermore, several disturbances caused by voltage instability problems have been reported in the literature [2], [5]. These events have motivated the development of tools to quantify the Voltage Instability Risk (VIR). The interest in evaluating the VIR has resulted in several papers related to VSPA [10]-[15]. In these publications, the VSPA has been carried out using two techniques: the State Enumeration Method (SEM) [11], [13], [15] and the MCSM [10], [12], [14]. They have been used to model the following uncertainties associated with the disturbances which cause voltage instability problems: peak load forecasting error and equipment unavailability (outages in generators, lines and transformers). The stochastic modeling of random disturbances produced probabilistic indices such as: bus and system VIR, bus and system expected VSM and expected load curtailments due to voltage instability problems. It is important to mention that these indices were estimated using two criteria to identify

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unstable states: unsolvability of the power flow equations or violation of the VSM limit. The unstable states associated with voltage controllability loss are not considered in the VSPA. Nevertheless, controllability loss problems have been reported in several voltage instability incidents, such as the disturbance of the South/South-East Brazilian system on 24 and 25 April 1997 [5]. Therefore, the main aim of this paper is to model the unsolvability and the controllability loss in the VSPA. The model is based on the combination of three techniques:

i) MCSM [8], [9]: to consider uncertainties associated with peak load forecasting errors and equipment unavailability;

ii) DMM [5]: to include controllability loss problems in the probabilistic indices associated with unstable states;

iii) Nonlinear OPF based on the Interior Point Method [4]: to assess unstable states associated with unsolvability of the power flow equations.

It is important to mention that the unstable states associated with the controllability loss can be also identified using the Modal Analysis [6]. However, the Modal Analysis has a computational cost higher than the one associated with the DMM. The disadvantage of the Modal Analysis is due to the computation of eigenvalues/eigenvectors to assess the voltage stability of a system bus. On the other hand, the DMM requires only backward/forward solutions, with the LU factors of the power flow Jacobian matrix, to carry out a nodal voltage stability analysis. The computational cost is a critical issue in VSPA since a large number of system states must be assessed to estimate the indices with an acceptable precision. Thus, the DMM was selected to identify controllability loss problems in the proposed method for VSPA.

The combination of the three techniques has been used to estimate the VIR and the Well-Being states probabilities [16], [17]. Furthermore, the proposed method has been used to evaluate the participation factors of the uncertainties and voltage instability mechanisms with regard to the VIR. These indices have been estimated for three test systems: two equivalent systems obtained from the Brazilian interconnected power system [18] and a modified version of the IEEE Reliability Test System [19]. The test results with the three systems demonstrate that the voltage controllability loss has significant impact on the probabilistic indices associated with unstable states.

The proposed method for carrying out the VSPA is described in Section II. The two techniques used in the voltage stability analysis, DMM and nonlinear OPF, are outlined in Section III. The definitions of the proposed indices for the VSPA are established in Section IV. The test results are in Section V. Conclusions are in Section VI.

II. THE VSPA METHOD

The voltage stability of an electric network is a function of parameters such as: load level, generation patterns and network topology. They are subject to uncertainties associated with load forecasting errors and component outages. Here, the uncertainties associated with network parameters were included in the VSPA through MCSM. The peak load forecasting error is usually modeled using a normal distribution [8], [9]. Consequently, it is possible to use a Box-Müller generator [9] to sample a system peak load for each system state selected by the MCSM.

On the other hand, the equipment unavailability was modeled considering that the component outages are independent and represented by a two state model. Consequently, the outage probability is the forced unavailability. Thus, the state of a component is sampled as [9]:

i) generate a random number X^{unif} with uniform distribution;

ii) $s_j^i = \begin{cases} 1\,(\text{up state}), \text{if } X^{unif} > U_j \\ 0\,(\text{down state}), \text{if } 0 \le X^{unif} \le U_j \end{cases}$

U_j is the unavailability of the component j;

s_j^i is the state of the component j in system state i.

The state of the components and the load level are combined to define a system state as $s^i = \left(s_1^i, s_2^i, \ldots, s_{NC}^i, L^i\right)$, where: NC is the number of components, L^i is the peak load for the state i and s^i is the ith sampled system state.

The system states sampled by MCSM may present network connectivity loss (islanding) due to circuit outages. Consequently, it is necessary to carry out topological processing to identify whether the original system was split into subsystems (islands) or not. Here, the topological processing is carried out using graph transversal techniques such as breadth and depth searches.

The generation of each island, identified in the topological processing, must be dispatched to satisfy its load. The dispatch is subject to the following constraints: active power balance equation and limits for the generators output power. In thermal systems, the dispatch is achieved using a merit order list of the incremental costs associated with the generators. That is, it is the result of the production cost minimization. On the other hand, in hydroelectric systems it is not possible to associate production costs with the generators. An alternative to overcome this difficulty is to carry out the dispatch through the minimization of the squared Euclidian distance (quadratic deviation) between the generators power output and a specified generation pattern. The pattern is determined in the short term (daily) scheduling of the hydroelectric plants [20]. It is possible to use relative weights for the power plants in the minimum deviation dispatch. The weights define the participation factor of each plant in the minimum deviation dispatch. Besides the dispatch, it may be necessary to carry out load curtailment to eliminate generation deficit in some system states.

After the load/generation dispatch in each island, it is necessary to compile the data required to carry out the power flow analysis in the sampled state. The compilation is associated with the following tasks: definition of the bus types (PV, PQ and Vθ), evaluation of the Mvar limits in buses with reactive power generation, elimination of isolated buses and infeasible islands (islands without proper load and generation, etc.).

The power flow analysis is the starting point for the voltage stability assessment of a sampled state. If the power flow algorithm converges for a solution, then the DMM is used to determine whether the current state has voltage instability problems caused by controllability loss. Otherwise, the Solvability Restoration of the Power Flow Equations (SRPFE) task is carried out using nonlinear OPF. The restoration is performed to analyze the severity of the voltage instability states associated with the unsolvability of the power flow equations. This information is very important for the system operators since it allows to identify whether or not there are states in which the unsolvability can be eliminated without load curtailment.

The sample of system states assessed with the DMM and by the SRPFE algorithm may be used to estimate probabilistic indices. The indices are evaluated through the sample average definition:

$$\tilde{E}(F) = \frac{1}{NS}\sum_{i=1}^{NS} F(s^i)$$

where:

NS is the number of system states;

$\tilde{E}(F)$ is the mean value of the index F;

$F(s^i)$ is the value of the test function associated with the index F in the state s^i. For example, if the estimated index is the Loss of Load Probability (LOLP), then $F(s^i) = 1$ when s^i is a failed state (if there is load curtailment in the state s^i), and $F(s^i) = 0$ otherwise.

The uncertainty of the estimate $\tilde{E}(F)$ obtained with the MCSM may be assessed by means of the coefficient of variation [9]. The coefficient is given by:

$$\tilde{\beta}(F) = \frac{\tilde{\sigma}(F)}{\tilde{E}(F)}$$

where:

$$\tilde{\sigma}(F) = \sqrt{\tilde{V}ar(F)/NS}$$

$$\tilde{V}ar(F) = \frac{1}{NS-1}\sum_{i=1}^{NS}\left[F(s^i) - \tilde{E}(F)\right]^2$$

$\tilde{V}ar(F)$ is the estimated variance of the index F;

$\tilde{\sigma}(F)$ is the estimated standard deviation of the index F.

In this paper, the coefficient of variation has been used as a stopping rule for MCSM. However, the maximum number of simulations is used as safeguard criterion to avoid an inordinate number of simulations being carried out when a specified precision is very small.

III. VOLTAGE STABILITY ASSESSMENT OF A SAMPLED STATE

A. DMM

The DMM [5] is used to identify whether a state has voltage instability problems caused by the controllability loss. The method is based on the linearized system of the power flow equations:

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} \qquad (1)$$

Putting the equations related to the bus i in the bottom of (1):

$$\begin{bmatrix}\Delta P_i \\ \Delta Q_i\end{bmatrix} = \begin{bmatrix}A & B \\ C & D\end{bmatrix}\begin{bmatrix}\Delta\theta' \\ \Delta V' \\ \Delta\theta_i \\ \Delta V_i\end{bmatrix} \qquad (2)$$

where, the submatrices A, B, C and D originated from a partition of full Jacobian matrix $[J]$. Assuming an incremental variation ΔP and ΔQ only in bus i under analysis ($\Delta P' = \Delta Q' = 0$), it is possible to eliminate the coupling between $[\Delta\theta' \ \Delta V']$ and $[\Delta\theta_i \ \Delta V_i]$ through Gauss elimination. Applying the procedure in (2):

$$\begin{bmatrix}\Delta P_i \\ \Delta Q_i\end{bmatrix} = [D']\begin{bmatrix}\Delta\theta_i \\ \Delta V_i\end{bmatrix} \qquad (3)$$

where: $[D']_{(2\times2)} = [D] - [C]*[A]^{-1}*[B]$

The equation (3) expresses the sensitivity relationships between voltage and power injection in bus i considering the whole system. From the determinant of D' matrix, it can be concluded that [5]:

i) ***det*[*D'*] > 0**: the bus i is operating in the stable region of the PV curve (upper half);

ii) ***det*[*D'*] < 0**: the bus i is operating in the unstable region of the PV curve (lower half), that is, the bus i has voltage instability problems caused by controllability loss;

iii) ***det*[*D'*] = 0**: the bus i is operating in the maximum loading point ("tip of the nose").

B. Nonlinear OPF

The SRPFE task is performed by the minimization of the power curtailments in the load buses subject to the following constraints: active and reactive power balance equations, limits on the active and reactive power generations and specified ranges for the voltages in a bus with reactive power generation. In this nonlinear OPF problem, the following control actions have been used for the SRPFE: active generation redispatch, voltage resettings in buses with reactive power generation and load curtailment (as a last resource).

The nonlinear OPF problem has been solved using the Interior Point Algorithm proposed in [4]. The main advantage of using the nonlinear OPF to solve the SRPFE problem is the ability of this approach to identify whether it is necessary to carry out load curtailments to eliminate the unsolvability. The identification is not possible when the solution of the SRPFE is based on Continuation Power Flow method [7], because the load and the generation are simultaneously reduced or increased in each predictor/corrector step.

IV. PROPOSED INDICES FOR VSPA

The main index used in the VSPA is the VIR. It expresses the occurrence probability of system states with voltage stability problems. In this paper, an unstable state is identified when the power flow equations have not solution or $\Lambda^{i}_{\min} \leq 0$, where $\Lambda^{i}_{\min}$ is the minimum value of det[D'] for all buses PQ and PV in the sampled system state *i*. Beyond the VIR, the VSPA proposed is also based on the Well-Being States probabilities [16], [17]. The Well-Being analysis has the objective of establishing of a link between probabilistic analysis and power system operation, which traditionally has been dominated by deterministic criteria such as the N-1. The link is based on the definition of Well-Being states, which are similar to the states used in the power system security assessment. Here, the deterministic criterion used to define Well-Being states is the occurrence of voltage instability problems. It was chosen because it has been used by the Brazilian independent system operator in voltage security studies [21]. With the established criterion, it is possible to define the following Well-Being states:

i) Health State: the power equations have a solution and $\Lambda^{i}_{\min} > 0$

ii) Marginal State: the power equations have a solution and $\Lambda^{i}_{\min} \leq 0$

iii) Emergency State: the power flow equations have not solution, but it is possible to restore the solvability without using load curtailments.

iv) Collapse State: the power flow equations have not solution and the solvability can only be restored by load curtailments.

From the test functions defined, it may be concluded that:

i) The voltage instability problems caused by unsolvability are considered more severe than those associated with controllability loss.

ii) The Well-Being states are defined in accordance with the severity of the voltage instability mechanisms, that is: controllability loss and unsolvability.

V. TESTS RESULTS

The proposed method for the VSPA has been tested in three test systems: two equivalent systems obtained from Brazilian interconnected power system (BTS-65 and BTS-107) [18] and a modified version of the IEEE reliability test system (MRTS) [19]. The main characteristics of the test systems are presented in Table I. The reliability data associated with the BTS-65 and BTS-107 have been obtained from [22].

The probabilistic indices used in VSPA have been estimated under the following conditions:

TABLE I. CHARACTERISTICS OF THE TEST SYSTEMS

Characteristic	**Systems**		
	MRTS	**BTS-65**	**BTS-107**
Installed Capacity (MW)	4304.0	17858.2	22080.2
Load Peak (MW)	3562.4	10102.1	12681.7
No. of buses	24	65	107
No. of circuits	31	141	230
No. of generators	40	65	103
No. of plants	10	14	23
No. of compensators	1	4	5

i) the load forecasting error (σ^{o}) is 5.0%;

ii) outages in circuits, generators and compensators have been considered in the VSPA;

iii) The pre-specified tolerances for the coefficient of variation in the BTS-65, BTS-107 and MRTS are equal to: 5.0%, 10.0% and 5%, respectively;

iv) The maximum sample size is 100,000 for the MRTS and 50,000 for the Brazilian systems.

v) The VSPA is carried out considering a two state model for generation failures. It is due to the lack of data associated with multi-state models in the Brazilian systems.

vi) The relative weights for each power plant of the Brazilian systems are based on the equivalent reactance from the bus in which the plant is connected. The inverse of the equivalent reactance is used in several Brazilian electric energy utilities as participation factor to allocate the load among the hydroelectric plants.

The computational effort (number of simulations and CPU time) to carry out VSPA in each test system, considering the conditions (i)-(vi), is shown in Table II. The results presented in the table have been obtained using a PC with Intel Core Quad CPU of 2.4 GHz and 3.25 GB of RAM.

TABLE II. COMPUTATIONAL EFFORT TO CARRY OUT THE VSPA IN THE TEST SYSTEMS

System	**No. of Simulations**	**Computational Time (min.)**
MRTS	42,401	4.5036
BTS-65	38529	7.3208
BTS-107	30313	15.9107

From the Table II, it may be concluded that the sample size required estimating a probabilistic index, with a specified precision, is independent of the system size (number of components). For example, the sample size for the MRTS (42401) is bigger than the one associated with the BTS-65 (38529), for a relative uncertainty of 5%. Nevertheless, the MRTS is about three times as small as the BTS-65. The effect is due to the number of simulations to be a function of the following parameters associated with a index: variance, specified tolerance and expected value [9]. The estimated values of the relative uncertainty (β) for the probabilistic indices evaluated for the three test systems are shown in Table III. From Table III, it can be concluded that the convergence of the MCSM is dominated by the probabilities of the Well-Being states. For example, the maximum relative uncertainties for the MRTS, BTS-65 and BTS-107 are associated with the following indices: P(Marginal), P(Collapse) and P(Marginal), respectively. This characteristic is due to the probabilities of these states have the smallest expected values among the estimated indices.

Additionally, the results of the Table II show that the CPU time for the VSPA in the BTS-107 is high. However, it is important to emphasize that the computational cost of the VSPA can be significantly reduced using the following strategies:

i) Reduction of the system size through the utilization of external equivalent to represent areas that have not voltage stability problems;

ii) Importance sampling methods based on cross-entropy to decrease the sample size required by the MCSM to estimate the probability of rare events [23].

TABLE III. COEFFICIENT OF VARIATION FOR THE PROBABILISTIC INDICES (IN PERCENTAGE)

Index	MRTS	BTS-65	BTS-107
VIR	0.8120	1.1401	1.2774
P(Health)	0.2905	0.2277	0.2583
P(Marginal)	4.9954	1.2431	9.9837
P(Emergency)	0.8624	4.5552	1.3566
P(Collapse)	4.1752	4.9994	5.0311

The main index used in the VSPA is the VIR. The VIR values for the MRTS, BTS-65 and BTS-107 are respectively: 26.3484%, 16.6446% and 16.8179%. The results demonstrate that the VIR for the three test systems is very large. However, the causes of the high risk values are not the same for the three test systems. This fact can be demonstrated through the evaluation of the participation factors of the uncertainties in the VIR. That is, the percentage of each type of uncertainty in the VIR. These participation factors allow carrying out a root cause analysis of the VIR oriented for the system uncertainties. The participation factors of the uncertainties in the VIR are presented in Table IV. There, the acronyms G, C, L and GC are associated with: generator and compensators outages, circuit contingencies (lines and transformers), fluctuations in the system peak load due to forecasting errors (without equipment in down state) and simultaneous failures of circuit and generators, respectively.

From Table IV, it may be concluded that:

i) the unstable states of the MRTS and BTS-107 are mainly caused by generator failures. This effect may be caused by the existence of a deficiency in the reactive power generation reserve. Consequently, there are not enough Mvar resources to correct the voltage profile in the contingency states;

ii) in the BTS-65, the main cause of the voltage instability problems is the load forecasting error. This result is an indicative that the current operating point in the BTS-65 corresponds to a heavily load condition. Consequently, small fluctuations in the system peak load result in voltage instability scenarios;

iii) the system where the transmission failures have more impact on the VIR is the BTS-65. Thus, it may be necessary reinforcements in the transmission network.

TABLE IV. ROOT CAUSE ANALYSIS OF THE VIR BASED ON THE SYSTEM UNCERTAINTIES

Uncertainties	MRTS	BTS-65	BTS-107
G	69.8980 %	17.6049%	57.4147%
C	0.9846 %	29.0816%	6.6104%
GC	4.2338 %	11.8821%	31.6987%
L	24.8836 %	41.4315%	4.2762%

The VSPA of the test systems has also been carried out using Well-Being indices. They allow a voltage stability analysis based on the instability mechanisms. Furthermore, the Well-Being analysis also enables the identification of unsolvable states which can be restored without using load curtailment. The probabilities of the Well-Being states for the three test systems are presented in Table V. They can be used to estimate the participation factors of the unstable Well-Being states (Marginal, Emergency and Collapse) on the VIR. That is, it is possible to use the probabilities of the unstable Well-Being states to carry out a root cause analysis of the VIR oriented for the voltage instability mechanisms. The participation factors of the Marginal, Emergency and Collapse states are shown in Table VI.

From Tables V and VI, it can be stated that:

i) the emergency state is the most likely state in the MRTS and BTS-107. In other words, the main cause of the voltage instability is the unsolvability. It is also demonstrated by the participation factors. The participation factors of the emergency state for the MRTS and BTS-107 are equal to 91.3802% and 90.3884%, respectively. That is, the largest participation factors of the emergency are associated with the MRTS and BTS-107;

ii) the maximum value of the probability of occurrence of the marginal state is associated with the BTS-65. Due to this, the largest participation factor of the marginal state occurs in the BTS-65 (86.4026%). That is, the unstable states are mainly caused by the controllability loss;

iii) the participation factors associated with the collapse state are small for the three systems. The largest value is 7.6501%. Consequently, even in the most unsolvable states, it is possible to restore a solution without using load curtailment. Therefore, the unsolvability of the power flow equations for the three systems is not too severe.

TABLE V. PROBABILITIES OF THE WELL-BEING STATES

States	MRTS	BTS-65	BTS-107
Health	7.3652×10^{-1}	8.3355×10^{-1}	8.3182×10^{-1}
Marginal	9.3630×10^{-3}	1.4381×10^{-1}	3.2989×10^{-3}
Emergency	2.4077×10^{-1}	1.2354×10^{-2}	1.5201×10^{-1}
Collapse	1.3349×10^{-2}	1.0278×10^{-2}	1.2866×10^{-2}

TABLE VI. PARTICIPATION FACTORS OF THE UNSTABLE WELL BEING STATES ON THE VIR

States	MRTS	BTS-65	BTS-107
Marginal	3.5535 %	86.4026%	1.9616%
Emergency	91.3802 %	7.4224%	90.3884%
Collapse	5.0662 %	6.1750%	7.6501%

Additionally, it is also important to assess the efficiency of the control actions used for the SRPFE. The assessment may be carried out by the evaluation of the participation factors of the unsolvable Well-Being States (Emergency and Collapse) with reference to the probability of unsolvability. The participation factors are presented in Table VII for the three test systems.

TABLE VII. EFFICIENCY OF THE CONTROL ACTIONS USED IN THE SRPFE

State	MRTS	BTS-65	BTS-107
Emergency	94.7471 %	54.5872%	92.1969%
Collapse	5.2529 %	45.4128%	7.8031%

In Table VII, it may be observed that the generation redispatch and the voltage set-point resetting in PV and Vθ buses are highly efficient to avoid load curtailments in the MRTS and BTS-107. On the other hand, these corrective actions were efficient in only 54.5872% of the unsolvable states in the BTS-65. Consequently, the unsolvability of the power flow equations is more severe in this system.

Finally, it should be mentioned that a restored solution by the OPF algorithm may have controllability loss problems. That is, the solution obtained by the SRPFE algorithm is in the unstable region (lower half) of the PV curve. The probabilities of a state having unsolvability and voltage controllability loss problems for the MRTS, BTS-65 and BTS-107 are respectively: 0.0684%, 2.0945% and 4.9682%. From these results, it may be noted that the occurrence probability of the two voltage instability mechanisms is significant in the Brazilian systems.

VI. CONCLUSIONS

A method of including unsolvability and voltage controllability loss in the VSPA was presented. It is based on the combination of three techniques: DMM, nonlinear OPF and MCSM. The main contributions of the proposed method with regard to existing approaches are: modeling of the two voltage instability mechanisms (controllability loss and unsolvability) in the VIR estimation, severity assessment of voltage instability states through the Well-Being Analysis and the inclusion of the main disturbances that cause voltage instability problems (equipment failures and load peak fluctuations due to forecast errors).

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