Large-scale Power System Security Monitoring and Enhancement based on Graph Computing Platform

***Abstract* - The voltage stability and line thermal limit are two major security issues when the system is operating in peak load hours or subjected to a disturbance. This paper proposes a model-based method for monitoring the voltage stability, based on the existing graph computing platform. When the voltage stability index of one or multiple buses exceeds the security limit, the demand response is activated in order to enhance the voltage security margin with the consideration of line thermal limit. The simulation study indicates that the stability monitoring and demand response scheme can effectively ensure the security index with relatively low computation workload. Therefore, it is applicable to large-scale Energy Management System (EMS).**

*Key words* - *power system security, voltage stability monitoring, thermal limit, demand response, security enhancement*.

# Introduction

The modern power system is developing into an increasingly complex and heavty-loaded system, with the integration of HVDC transmission lines and large amount of renewable energy sources [1]-[3]. The voltage stability and line thermal limit are two major concerns when the system is operating in peak load hours or subjected to a disturbance, such as a line outage or generator outage. In particular, the system voltage stability cannot be directly measured as thermal limit does. The purpose of voltage stability monitoring (VSM) is to identify the degree of stability and predict the maximal deliverable power to a load bus. If the stability margin is lower than the limit, necessary load reduction should be conducted to prevent the voltage collapse, or even cascading failure [4]-[5]. The VSM methods are classified into model-based and measurement-based method [6].

Continuation power flow (CPF) is a common model-based algorithm to estimate the steady-state voltage stability margin [7]. CPF is successful in power system planning, but is time-consuming for power flow calculations and not always a good choice for online VSM of a large-scale system [8]. With the fast development of phasor measurement units (PMUs), measurement-based VSM has received significant attentions in the past decade. The impedance matching method was proposed in [9]-[10]. The main idea can be summarized as: The system Thevenin equivalent (*Zth*) seen by a local bus is determined by the voltage and current phasor of two distinct points, which is obtained by PMU. The load impedance *Zl* is determined by the voltage and current phasor. In normal operating condition, Local Thevenin Index (LTI) which is defined as the ratio between |*Zth*| and |*Zl*| measures the voltage stability margin [10]. Voltage instability happens if the ratio equals to 1. In spite of its simplicity, this method has some limitations in the industry application. The estimation of LTI relies on the quasi-steady state of the system. However, in a contingency, the system experiences a series of changes, such as line tripping, generators reaching vars limit. Consequently, the bus voltage can oscillate and causes significant error of LTI [11]-[12]. Besides the above VSM method based on local PMU data, more recent work on wide-area PMU measurement or hybrid VSM methods are proposed [6], [11], [13]-[17]. The Sensitivity-based Thevenin Index (STI) was proposed in [11], [15]. Although its definition is the same as LTI, the computation is based on the system Jacobian matrix and provides an accurate estimation of the stability margin.

Furthermore, even if the line power flow is not large enough to cause any voltage instability, there is still a possibility that the line flow exceed the thermal limit during peak load hours or under N-1 contingency [18]-[19]. Therefore, voltage stability and line thermal limit should be both considered for identifying the system security. If either of them is violated, system operator is supposed to quickly and accurately identify this security violation and make proper control actions to enhance the system security.

In the industry application, the traditional online VSM usually update the data every 15 minutes or larger [x]. However, the system blackout usually happens within several minutes, and this time interval too large for the operator to catch the cascading events and take necessary actions to prevent the voltage collapse [x]. In recent years, the high performance, parallel computation technology can solve the power flow very fast [20]-[21]. The demand response (DR) has great potential in providing frequency regulation support and security enhancement [22]-[23]. Reference [23] proposed an event-driven DR scheme for security enhancement. However, the impact of load variation on line power was not considered. The corrective voltage control considering demand response was proposed in [24]-[25]. The generation and load were dispatched together in order to keep the voltage stability margin. The control strategy was comprehensive but did not show a method of updating the VSI.

Based on the existing graph computing platform, this paper proposes a modeled based VSM scheme that obtains the accurate LTI with relatively low computation workload. Furthermore, a DR scheme is proposed for enhancing the system security with the consideration of voltage stability margin and transmission line capacity. The proposed VSM and DR scheme is applicable to the Energy Management System (EMS) of large-scale power systems.

The remaining part of the paper is organized as follows. Section 2 provides a general description of graph computing platform for fast power flow calculation. Section 3 discusses the methodology of calculating two security indices, voltage stability and line thermal limit based on the graph computing platform. Section 4 proposes a demand response scheme for system security enhancement. The verification study is presented in Section 5. Finally, Section 6 concludes the whole paper and discusses future research directions.

# Graph Computing Platform for Power Flow

## Graph Computing for Fast Power Flow

Graph theory is the study of graphs, which are applied to modelling relations between objects. A graph is a collection of vertices and edges, representing objects in a system and relations between objects, respectively. Graph database uses graph structures to represent and store data in vertices and edges. Such database allows data to be linked directly, and retrieved with one operation. In recent years, the graph computing technology enables the fast power flow and state estimation. Generally, power system is comprised of power generation, power delivery, power distribution, and power consumption. The four components are categorized into two types: (1) bus-attached, and (2) line-attached. For example, generators and loads are connected to buses and regarded as power injections at buses. Then, they are taken as bus-attached components. Transmission lines connect the buses and are considered as line-attached parts [21].

Global Energy Interconnection Research Institute North America (GEIRINA) has developed an EMS based on graph computing. The EMS platform can realize power flow calculation of thousand-bus-level system within 0.1 second. The power flow result is updated every 4 seconds. During the time interval, the power flow, state estimation, security monitoring and contingency analysis can be completed. Based on this high efficiency computing platform, the system voltage stability can be monitored with the latest measurement data. Then, the necessary control actions can be made timely if the system is experiencing an extreme heavy load condition or disturbance.

## Description of a Provincial-level System

The Sichuan transmission system (in China) contains 2637 buses, xx lines and xx transformers that are equal or higher than 110kV voltage level. The base power for power flow calculation is 100MVA. In the yearly load profile, the system peak load is (32.30 + *j*5.512)GVA, the largest PQ load in the system is (4.592 + *j*1.973)GVA, and the highest-loaded line is (10.75 + *j*2.188)GVA. The network topology of 500kV-level or higher transmission lines is shown in Fig. 1.

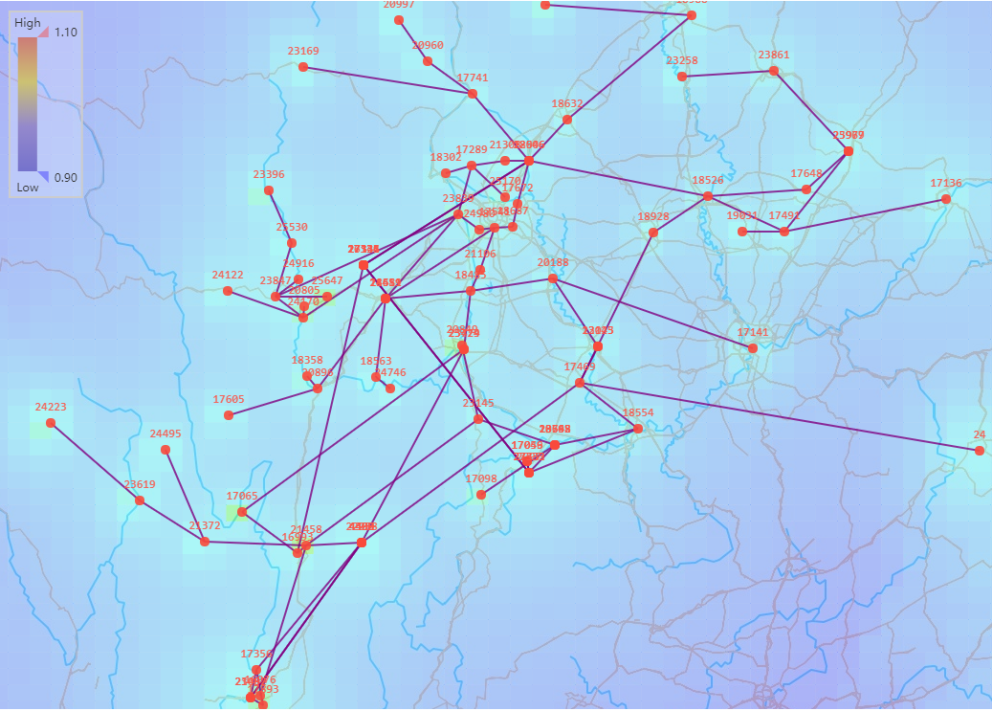


Fig. . Main structure of Sichuan 2637-bus transmission system.

# Online Computation of System Security Index

This section introduces two main security indices, voltage stability index (VSI) and line thermal limit. Subsection 3.1 compares the accuracy and time consumption of two online computation methods of VSI. Also, the correlation between VSI and load margin are analyzed. Subsection 3.2 introduces the Generation Shift Factor for calculating the line flow increment. These two indices are the basis for the demand response program.

## Voltage Stability Index

*3.1.1 Calculation of Voltage Stability Index*

As is shown in Fig. 1, the external system seen from a load bus can be reduced to a Thevenin equivalent, with a voltage source *Vth* and an impedance *Zth*. In principle, two subsequent phasor measurements of the pair *V* & *I* can be used to compute *Zth* under the assumption that *Vth* and *Zth* keep constant during the time interval between the two subsequent measurements [26]. The Thevenin equivalent parameters and conventional LTI can be determined by -.



Fig. 2. System Thevenin equivalent circuit.









where  and  represent the voltage and current phasor when the system loading level is *PLi* + *jQLi*, respectively.  and  represents the voltage and current phasors when all the loads increase with the same load scaling factor ∆*λ* (∆*λ* is usually lower than 0.05). LTI is called measurement-based LTI if the voltage and current phasors are obtained by local measurement, and called model-based LTI if the phasors are obtained by power flow calculation. Furthermore, if ∆*λ* approaches 0, the LTI is the most accurate. A sensitivity-based Thevenin index was proposed in [11].



The terms *dV*/*dλ* and *dθ*/*dλ* are the sensitivities of the voltage magnitude and the phase angle with respect to ∆*λ*. The STI and LTI are visualized in Fig. 3. Point A is the present operating point, point C corresponds to a load increment (∆*λ* > 0). The LTI derived using the ∆*λ* is directly related to the slope of the secants AC. As the ideal value of the LTI occurs when the ∆*λ* → 0, this corresponds to the slope of the tangent at point A (which is same as the sensitivity). And thus, the sensitivities at an operating condition can be used to calculate the ideal LTI at a particular bus.



Fig. . A PV curve indicating that the slope of tangent at a point A.

The slopes can be obtained by the Jacobian matrix.



where ***P*** and ***Q*** are the vectors of real power and reactive power, respectively; ***θ*** is the voltage angle of the PQ and PV buses; and ***V*** is the voltage magnitude of PQ buses. The submatrices ***fθ*** and ***fV*** are the partial derivatives of the active power flow injection expressions with respect to the angles and voltages and can be extracted directly from the Jacobian matrix at that operating point (***P***0, ***Q***0). Similarly, ***gθ*** and ***gV*** correspond to the partial derivatives of the reactive power flow.

In order to compute *dV*/*dλ* and *dθ*/*dλ*, we let . Then, is transformed into



The sensitivity terms can be obtained by .



Substituting to gives STI, which is an accurate value of LTI.

*3.1.2 Selection of VSI Computation Method for Large System Monitoring*

The computation of is based on the Jacobian matrix. Since our online monitoring system adopts fast decoupled power flow method instead of Newton Raphson power flow, additional efforts is required to compute the Jacobian matrix and its inverse matrix after the power flow calculation. In fact, since the fast decoupled power flow only takes less than 0.1s, we can also do fast decoupled power flow twice to obtain LTI. If ∆*λ* is small (e.g., 0.01), LTI can approximate STI with high accuracy [11]. Therefore, it is necessary to compare the accuracy and computation time of LTI or STI in order to determine which is more suitable for large system voltage stability monitoring. The computation process and time consumption of LTI and STI are shown in Fig. 4. It is noticed that the voltage phasors obtained by the last-step power flow is the initial guess of the current-step power flow. Therefore, the iteration can usually converge in 2 steps.



Fig. . Computation procedure of LTI and STI.

The test case is Sichuan 2647-bus system. The computer has xGB memory, xGHz frequency. In the four simulation scenarios, all the generation and loads are multiplied by 30%, 70%, 100%, and 130% of the base case, respectively. In the base case, we select 204 PQ buses (called “large PQ buses”) with *P* > 0.5 p.u. and rank their STIs in ascending order. In other scenarios, the STI and LTI values are also arranged in this order. The result shown in Fig. 5 confirms the LTI is very close to STI. Meanwhile, it can save xx% computation time. Therefore, model-based LTI for the online monitoring application.

The largest STI in four cases are: 0.111, 0.300, 0.488 and 0.743, respectively.



Fig. . Comparison of voltage stability index of PQ buses.

*3.1.3 Voltage Stability and Load Margin*

Based on Subsection 3.1.2, LTI has the advantage of low computation workload and is applicable to online voltage stability monitoring with high sampling rate. However, when the loading level is quite high and close to the critical point, LTI cannot provide direct guidance to the further control actions. This paper proposes a hybrid method for voltage stability monitoring. If the LTI is lower than a threshold *LTIsecu*, the system is secure and not action is needed. If not, the load margin is calculated in order to determine whether the demand response should be activated. At the operation point, the maximal deliverable real power to a bus is calculated by [12].



where *δ* is the power factor angle of the load. The load ratio is defined as the ratio between current real power load and the maximal deliverable power, given by .



A sensitivity study is conducted to show the relationship between the LTI and load margin. Assume the Thevenin equivalent voltage source and impedance are *Vth* = 1.0 pu, and *Zth* = 0.02 + *j*0.1. The PV curves and LTI curves of different load power factors are shown in Fig. 6. The figure indicates for the same loading level (i.e. 85% of *Pmax*), the LTI slightly increases when the power factor change from lagging to leading. Since the power factor in real system ranges between 0.95 lagging and 1.0, we choose *LTIsecu* = 0.50 as the threshold of checking whether to activate the DR. In the low load condition (below 85% of *Pmax*), however, LTI is a good indicator of the load ratio because it is roughly linear to the system loading level.

## Line Thermal Limit

*3.2.1 Definition of Generation Shift Factor*

The thermal limit is another security constraint of the system. In this paper, we only consider the real power limit for simplicity. Thus, the generation shift factor (GSF) is applied to calculate the line power flow in response to the nodal injection. The line flow is given by [27].



For example, GSF = ±0.35 indicates that 1MW net power injection at bus *i* leads to 0.35MW power flow increase/decrease at line *l*. Due to the complexity of the network topology and large variation of line impedance, the values in the GSF matrix vary between –1.0 to 1.0.



Fig. . Correlation between LTI and PV curve.

*3.2.2 Selection of Sensitive Lines*

Theoretically, in a network with *N* node and *M* lines, all the GSF values form an *M* × *N* matrix. In the industry, however, we are only interested in the GSF of heavy loaded lines with regard to 204 large PQ buses. In this study, the heavy loaded line is defined as the real power larger than 10 p.u.. As a consequence, 21 out of xx lines are selected.

Although the transmission network is generally a highly-meshed network, there are still some radial areas. The example of mesh line and radial lines are shown in Fig. 7 (a) and Fig. 7 (b), respectively. The GSF in the different topologies should be considered separately.

* *Line in the radial area*: If the line *l* is in a radial area, then *GSFl,i* = ±1 only if bus *i* is at the downstream side of this radial line. Otherwise, *GSFl,i* = 0. Fig. 8 (a) shows the ranked GSFs of representative line with regard to the 204 selected buses. For line 9-5, all the *GSFl,i* values are zero because no large PQ buses are located in the downstream of line *l*.
* *Line in the mesh area*: If the line *l* is in a meshed area, then –1 < *GSFl,i* < 1. According to the definition of GSF, whether the load reduction increases or decreases the line flow depends on the positive-negative sign of *Pl* and *GSFl,i*. If *Pl* × *GSFl,i* < 0, then the load reduction (net power injection) at bus *i* reduces |*Pl*|. If *Pl* × *GSFl,i* > 0, then the load reduction at bus *i* even increases |*Pl*|. In order to simplify the representation, we define the direction of line to ensure *Pl* ≥ 0. Consequently, *GSFl,i* < 0 means that load reduction at bus reduces *Pl*, and the vice versa. Fig. 8 (b) also shows the ranked GSFs of representative line with regard to the 204 selected buses.

Fig. . Examples of line connection: (a) line in radial area; (b) line in the mesh area.

During the peak load hours, some lines might be overloaded. When the system operator determines the load reduction, they should consider whether the load change can make some lines exceed the thermal limit. The lines with heavy load and high GSF value should be considered in the DR scheme. Therefore, the transmission lines that are both heavy-loaded and sensitive to bus injection should be selected as “critical lines”. The critical line list (CLL) is defined as follows:



where *Nline* is the set of all transmission lines. Finally, 14 critical lines are selected for the DR scheme. The remaining 7 heavy-loaded lines are excluded from CLL because their power flow is extremely insensitive to the power injection change of 204 large PQ buses.



(a)



(b)

Fig. . Examples of line GSF: (a) line in radial area; (b) line in mesh area.

# Demand Response for System Security Enhancement

In this section, a DR scheme is proposed in this section in order to enhance the system voltage security and line flow security. The amount of load reduction is determined by the load margin and line thermal limit.

## Demand Response Scheme

A security-based optimization model is proposed. The DR is activated if only either of the following condition is satisfied.

* The load ratio at bus *i* exceeds 85%. It should be noticed that the monitoring system starts calculating *Pmax* when LTI is higher than 0.5.
* The power flow of any critical line *l* exceeds the thermal limit.

The objective function is to minimize the expense for interrupting the loads.



where *ci* is the cost of interrupting load *i*, *PDR,i* is the *i*-th load that is available for load reduction. At each load bus, the load reduction amount should obey the DR constraint. because only the interrupted load (e.g., air conditioners, electric water heaters) can be turned off.



If *PLi* > 0.85*Pmax,i* is detected, the load reduction should be large enough to bring the load within the security region.



where *Pmax,i* is estimated by . After the load reduction, the power flow of Line *l* is modified. The new power flow should obey the thermal limit:



It should be noticed that DR scheme is implemented by DC power flow, which ignores the reactive power. In fact, the system operator is not able to control the Var injection at a bus, because the local Var compensation devices are always adjusting its output according to the measured voltage. To simplify the study, we assume the power factor of the interruptible load equals to the power factor of that load bus.

The overall security-based DR scheme is summarized in Fig. 9. The first part is the offline computation, which provides the online monitoring and DR with basic parameters. The critical lines and major load buses are selected based on the proposed method in Section 3.2. The second part is online monitoring. In every time step (4 second), the EMS solves the AC power flow and calculate LTI. If the voltage security limit is violated, the load margin will be calculated. If either the voltage or thermal limit is violated, the DR will be activated. An optimization of load reduction is done, considering the requirement of voltage security and line limit. Furthermore, since the system operating condition keeps changing, *Pmax* of a load bus is not a constant. If the load margin of a bus is brought larger than 10% after load reduction, it may still fall below 10% in the next few steps. Then, the load reduction will be conducted according to the latest load margin. The load reduction is implemented by raising the temperature setting for central air conditioners in commercial buildings.



Fig. . Optimization of load reduction.

# Case Studies

This section presents the simulation study result of Sichuan 2647-bus system. The thermal limits of the critical transmission lines are shown in Table 1. Table 2 lists the parameters of 10 representative large PQ loads (the total number is 204). In each PQ load, we assume that 5% of the real power load is available for demand response. The cost is defined as the product of cost coefficient and standard cost *C*0. According to the previous studies [23], *C*0 is chosen as $200/MW.

Table 1. Thermal limits of critical lines.

|  |  |  |  |
| --- | --- | --- | --- |
| Line no. | Thermal limit (pu) | Line no. | Thermal limit (pu) |
| 2-1 | 74 | 101-185 | 34.5 |
| 10-5 | 32 | 119-155 | 27 |
| 5-408 | 36 | 119-580 | 30 |
| 5-410 | 33 | 150-224 | 38 |
| 89-15 | 31.5 | 185-239 | 80 |
| 100-101 | 78 | 224-241 | 32 |
| 101-119 | 35 | 342-185 | 39.5 |

Table 2. Parameters of large PQ buses.

|  |  |  |
| --- | --- | --- |
| Bus no. | Current power (pu) | *ci* (*C*0) |
| 11 | 55.11 + *j*23.67 | 0.91 |
| 16 | 10.41 + *j*0.78 | 1.26 |
| 33 | 2.55 + *j*0.88 | 1.23 |
| 126 | 2.32 + *j*0.52 | 1.05 |
| 139 | 2.50 − *j*0.11 | 0.82 |
| 250 | 2.64 − *j*0.39 | 0.88 |
| 258 | 1.41 + *j*0.11 | 0.84 |
| 376 | 41.09 + *j*16.89 | 0.84 |
| 384 | 2.40 + *j*1.04 | 0.80 |
| 548 | 0.91 − *j*0.01 | 1.29 |
| … | …. | … |

Assuming at a snapshot, the extreme heavy load happens is considered 120% of system based loading level. Then, the system total load is (38.76 + *j*6.61)GVA. The AC power flow indicates that 128 buses have LTI larger than 0.50 and one line exceeds the thermal limit. Then, the load ratio is calculated and arranged in ascending order. The top 40 load ratio (denoted as selected PQ buses) is shown in red dotted curve of Fig. 10 (a). Based on the proposed DR scheme, the load of 37 buses is reduced. The total load reduction amount is 0.607 pu (60.7MW) and the total payment is 61.0*C0*. As a consequence, the load ratio of all selected PQ buses is brought below the 85% security limit, shown in green dotted curve of Fig. 10 (a). The voltage magnitude of the selected PQ buses is presented in Fig. 10 (b). They are slightly increased by load reduction.

The real power flow of the critical lines before and after DR is shown in Table 3. Due to the diversity of GSF, the line flow can be increased or decreased after load reduction. In particular, power flow of line 119-155 exceed the limit before DR. It is decrease by 0.26 pu. Line 224-241 touches the limit after DR.



(a)



(b)

Fig. . Indices of large PQ buses before and after DR: (a) load ratio; (b) voltage magnitude.

# Conclusion and Future Work

This paper proposes an online security monitoring methodology and DR scheme for security enhancement. The online VSM is based on the newly-developed, high-performance graph power flow computing platform. Therefore, the voltage stability can be accurately estimated with a small time step. The contribution of this paper can be summarized as follows.

Table 3. Line flow of critical lines (before and after DR).

|  |  |  |  |
| --- | --- | --- | --- |
| Line no. | Line real power flow | | |
| Before DR (pu) | After DR (pu) | Change (%) |
| 2-1 | 69.17 | 69.17 | 0 |
| 10-5 | 30.51 | 30.51 | 0 |
| 5-408 | 27.40 | 27.39 | -0.001 |
| 5-410 | 27.68 | 27.68 | 0 |
| 89-15 | 28.57 | 28.28 | -1.00 |
| 100-101 | 66.40 | 66.41 | 0.001 |
| 101-119 | 32.69 | 32.58 | -0.34 |
| 101-185 | 35.49 | 35.60 | 0.31 |
| 119-155 | 28.26 () | **28.00** | -0.92 |
| 119-580 | 27.84 | 28.02 | 0.58 |
| 150-224 | 35.16 | 34.34 | -2.33 |
| 185-239 | 76.68 | 76.06 | -0.81 |
| 224-241 | 31.76 | **32.00** | 0.76 |
| 342-185 | 37.94 | 37.89 | -2.76 |

* A model-based VSM scheme is proposed. In normal condition, the LTI is updated every 4 second with high accuracy and relatively low computation workload. When LTI exceed the threshold, the control center needs to calculate the maximal deliverable power.
* The critical lines are selected based on their GSF to large PQ buses. If a line is sensitive to the power injection change of large load buses, it should be included in the optimization model. Consequently, the number of line constraint equations in the optimization model is greatly reduced, so is the computation workload.
* A DR algorithm is proposed to enhance the system security under heavy load conditions. The DR can effectively increase the load margin and prevent the line flow violation.

Overall, the proposed monitoring and enhancement technique satisfy two requirement of large-scale power system monitoring: being accurate and fast. It makes full use of the advantage of the graph computing platform and provides the system operator with an effective tool. The future work is to extend the security monitoring and DR scheme to N-1 contingency.

# Appendix

In an *N*-node system, the DC power flow function is:



where ***B’*** is the nodal admittance matrix and ***Pinj*,*k*** is the vector of nodal injection. The *k*-th component of ***Pinj*,*k*** is 1 and others are 0.



The nodal voltage angle is solved by



The GSF is calculated by



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