SIPS development method and busbar splitting scheme supported by PMU technology

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Abstract**—***Research presented in this paper is part of the idea for developing smart transmission grid (STG) supported by system integrity protection schemes (SIPS) based on phasor measurement unit (PMU) technology. The main objective of SIPS is to monitor the state of power transmission networks in real-time and if needed in emergency cases to undertake advanced actions.*

Contribution of this paper is new SIPS development method and busbar splitting scheme supported by synchronized phasor measurement technology (SPMT). Proposed method gives detail description how to develop SIPS through several steps, as well as the simulation of their operation. It is based on heuristic approach and detailed AC power flow analysis.

Busbar splitting scheme is described through its activity and initiation conditions in this paper. Initiation model is given in the form of graphical representation with its releasing and blocking conditions.

Developed method application to the IEEE 14 busbar system is given after its defining. Carried out tests show that developed method can mitigate potential overloads of the observed network part by using suggested busbar splitting schemes.

Keywords—smart transmission grid, power system analysis, system integrity protection schemes, synchronized phasor measurement technology

I. INTRODUCTION

Paper [1] highlights the need for providing research on impacts of renewables on electrical power system (EPS) and the corresponding protection and control strategies in order to mitigate the negative effects. These requirements are trying to be reached with the development of smart transmission grid (STG). STG implies performance of automated processes based on measurement, control, protection and telecommunication systems supported by smart technologies in order to maintain a secure power network state. According to [2] one of the solutions for large scale renewable integrations is to increase the flexibility of the EPS by using system integrity protection schemes (SIPS). Advanced control and SIPS are specific areas where significant improvements can be achieved using synchronized phasor measurement technology (SPMT) according to [3]. The mentioned technology was developed back in the 1980s [4]. Development of smart technologies placed increasing demands on the speed of data exchange and processing [5]. Biggest advantage of SPMT is transferring large amounts of data from different parts of the EPS in real time that are synchronized with GPS timestamp.

Undertaken research within the presented paper refers to several related problems:

- congestions in parts of the power transmission network due to the electricity market conditions of its controlling [6],
- high share of electricity production from renewable sources which is characterized by variable generation and difficult scheduling [7],
- changes in the nature and structure of electricity consumption (electrical vehicles etc.),
- coordination of local relay protection systems in different parts of the EPS [8].

Solutions to specified research problems are being looked up with the application of SPMT in the form of developing SIPS. The research hypothesis is defined as follows: development and use of SIPS supported by SPMT can maintain the integrity of larger part of EPS, improve coordination of local relay protection systems and mitigate potential congestions in the power network.

II. SYSTEM INTEGRITY PROTECTION SCHEMES

In 1996 a report on special protection schemes was published [9]. Report included more than 100 protection schemes used around the world. It was determined that such schemes cannot be called special no more because many participants use them. Instead of current naming it was proposed to use SIPS or remedial action schemes. In 2009 a report on SIPS was published [10]. According to report the SIPS deal with congestion, thermal overload, voltage, frequency and angular instability problems. Stated problems can be mitigated using different types of protection schemes. Busbar splitting schemes together with overload and congestion mitigation schemes are studied within this paper.

Selection of the “proper” busbar for busbar splitting scheme application in order to mitigate overloaded parts of the network is subject of many studies. There are many papers like [11], [12] and [13] that use different optimization methods for selection of the busbar such as linear, mixed integer linear, Benders decomposition etc. Selection of the busbar based on heuristics methods and then performing AC power flow analysis is chosen after reviewing the developed methods.

Special protection schemes are defined in [9] as schemes designed to identify specific events that cause unusual problems in the operation of the EPS and to undertake advanced predefined measures that will neutralize the detected events. SIPS supported by SPMT were developed as part of carried out research which major advantage is operation over a wide area (Fig. 1).

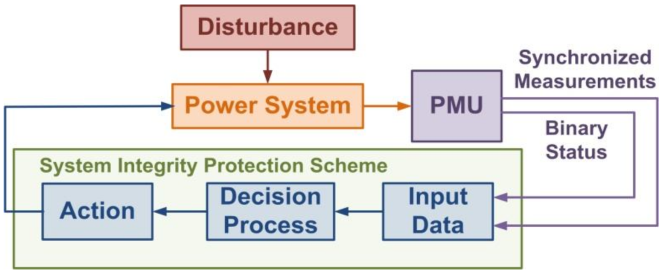

Fig. 1. *SIPS based on synchronized measurements*

III. SIPS DEVELOPMENT METHOD

SIPS are designed on the basis of analysis of the power system by defining requirements that they must meet. They are made based on power system's response to the recorded events or congestions. A new method for developing SIPS was created within carried out research based on security assessment, heuristic methods and AC power flow analysis. Flowchart of created method is shown in the figure below (Fig. 2).

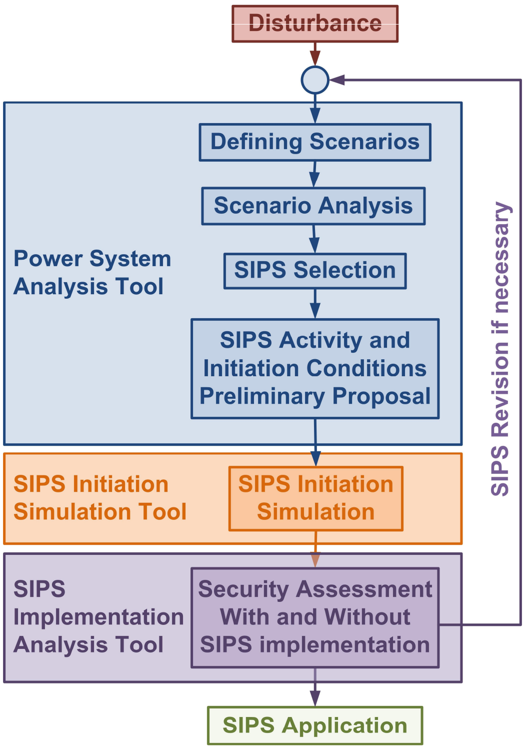

Fig. 2. *Flowchart of created method*

A. Disturbance as idea for SIPS development

Unpredictable disturbances or events in the network indicate the need for a detailed analysis of the power system. For such disturbances or events it is required to record all input parameters and system responses that can be analyzed using the specialized tools for power system analysis. Large disturbances or events in the power network can surely serve as idea originators for making SIPS.

B. Defining scenarios for power system analysis

The first step in SIPS development is to define a number of scenarios that include representative disturbances in the observed part of the system. There are different principles for determining scenarios for the analysis of power networks. Principles can be applied to seasonal (summer/winter), hydrological (good/bad hydrology) or day criteria (night/day) depending on many different network factors: the location of generating units, topology and scheduling of the transmission network, load distribution etc. Selection criteria for defining analysis scenarios depend on experience and expert knowledge of the observed part of the power system.

C. Scenario analysis

The second step in SIPS development relates to power system detailed analysis. Performing of AC power flow analysis is suggested because current application of described method is designed to perform offline analyses that are not time-critical, unlike some faster analysis that can be used in real time applications like DC power flow analysis [14]. It is recommended to analyze the basic conditions of each individual scenario defined in the previous step. These analyses will indicate the initial potential risks of the observed part of the network. It is necessary to analyze in detail each potential initial risk, i.e. high network load or voltage and angular deviations.

After analyzing basic conditions of each scenario and defining the initial potential risks in terms of high loading or voltage and angular deviations of the observed parts of the network, N-1 analyses can be accessed. Contingency analyses (N-1) can be extended to multiple element outages if necessary in the form of N-k analyses where k denotes the number of excluded elements.

It is recommended to perform N-1 analyses of each scenario for all elements in the close proximity to the endangered ones defined as the initial potential risks. In the analyzing process it is necessary to record all the N-1 or N-k analyses which have caused significant load increase of individual network elements or caused their unallowed loads.

D. SIPS selection

During selection of any kind of protection scheme it is necessary to have expert knowledge of the existing local relay protection system in order not to unnecessarily disturb its coordination by implementing new protection schemes. Mutual local relay protection and SIPS coordination will lead to successful mitigation and prevention of possible disturbances over a wide area and maintaining the security and integrity of the system.

There are different types of SIPS, which are in more detail described in the report [10]. SIPS researched in this paper are focused on corrective busbar splitting schemes that maintain the existing level of power system generation and loads. SIPS that don't maintain existing level of power system generation and loads, like load shedding and generation reducing schemes, will be studied in future works where there is no possibility of using busbar splitting schemes.

Busbar splitting schemes are characterized by retaining all elements connected to the power network. They use the principle of load redistribution in order to mitigate the load in the endangered parts of the network. In case of their usage there should be no consequences for participants connected to the network.

Congestion mitigation by changing the network topology essentially refers to the separation or integration of the electrical power system in differently connected network parts. System separation or integration is performed by separating or integrating different busbar systems or their sections in parts where their primary and secondary equipment design allows it. It is important to emphasize that any separation or integration of the system will impact more or less on power flows and voltage conditions in the observed part of the network. In case of implementing any considered measure it is important to carry out detailed system security analysis.

While developing busbar splitting schemes it can happen that none of the analysis indicates the possibility of making any busbar splitting action that while mitigate observed event. This can happen for various reasons, such as: the primary system is not built flexibly enough, secondary systems cannot adequately respond to requirements of developed model or other. In these cases it is recommended to seek mitigation solutions in other SIPS, even those that are not maintaining the existing level of power system generation and load.

E. SIPS activity and initiation conditions preliminary proposal

While defining SIPS it is necessary to assign each scheme with a specific unique label. Apart from the assignment of the unique label, it is necessary to describe the scheme in detail. Description implies defining substation and highlighting the type of SIPS. If busbar splitting scheme is chosen, it is necessary to define exactly which element needs to be connected to which busbar. Template for defining busbar splitting scheme is given in Table I.

TABLE I. TEMPLATE FOR DEFINING BUSBAR SPLITTING SCHEME ACTIONS

SIPS	SIPS Label
Substation	Substation name
Busbar 1	List of bays that needs to be connected to busbar 1
Busbar 2	List of bays that needs to be connected to busbar 2
…	…
Busbar N	List of bays that needs to be connected to busbar N

Heuristic method is based on the assumption that there are always two basic ways of relieving overloaded lines. They can be relieved with splitting the busbar from which energy comes or into which energy goes. To determine the possible combinations of busbar splitting it is necessary to determine the power flow directions of all elements connected to the busbars at the beginning and end of the overloaded line. The power flows in the observed busbars can also help in choosing the possible splitting combinations.

Possible splitting combinations are assumed using combinatorial principles and tested with the use of power system analysis tools until adequate topology that reduce the load of the observed network part are found. If tests indicate more suitable topologies the choice of recommended option is performed by comparing the security assessments in the last step of the given method.

Defining initiation conditions of busbar splitting scheme consists of defining two sets of conditions that will uniquely determine the initiation of necessary actions. The first group of conditions refers to the comparison of actual analog measured values obtained using synchronized phasor measurement units with predefined values specified on the basis of the detailed analysis. Another group of conditions refers to the comparison of the required connected or disconnected status of individual elements in a network with predefined ones also based on detailed analyses. Both sets of conditions consist of their elements for starting or blocking the busbar splitting scheme. The launching principle of a single scheme lays in the fact that all conditions must be satisfied in order to run it (Fig. 3). In special cases it is possible to allow launching of the model although all conditions are not met. Mentioned case isn't discussed in this paper, but can be used as a topic for future research.

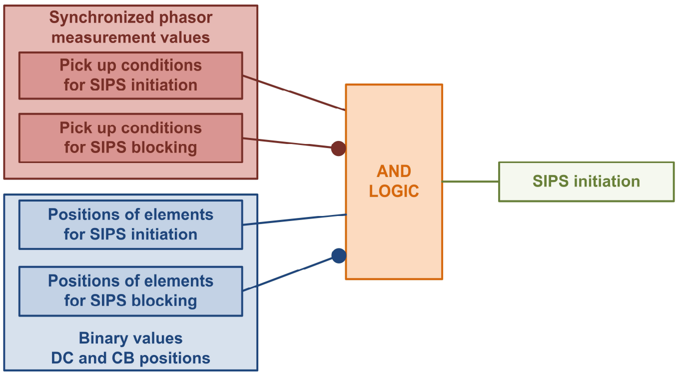

Fig. 3. *SIPS initiation model*

F. SIPS initiation simulation

SIPS initiation simulation can be accessed after defining their preliminary activities and design requirements. Matlab environment was used as a simulation tool for this paper's research. It is allowed to revise designed SIPS with the defined requirements after simulations, if certain irregularities in their functioning are noticed. A template for simulation of busbar splitting schemes in Matlab environment is given in Fig. 4.

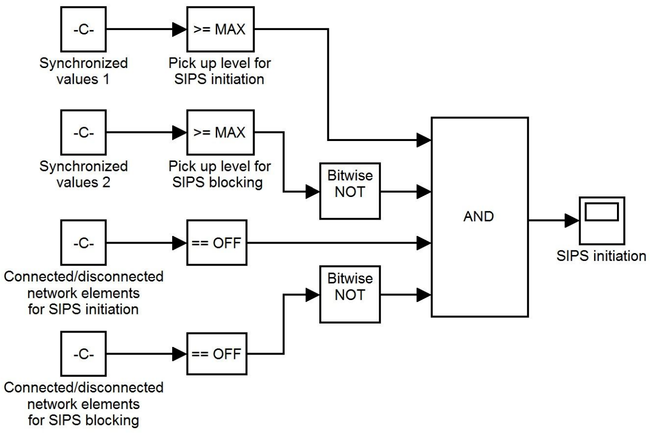

Fig. 4. *Matlab simulation model*

G. *Power network security assessment with and without SIPS implementation*

Each SIPS application will more or less influence on power flows and the voltage conditions in the observed part of the network. For this reason it is important to carry out detailed analysis of the entire system after the implementation of SIPS. Analysis presented in this paper consists of comparing voltage conditions and power flows together with generation, consumption, exchange and loss levels with and without use of designed SIPS. Each of mentioned comparisons is presented as graphical chart from which it is possible to clearly allocate the advantages and disadvantages of particular schemes. Doubts about choosing the "right" scheme come down to choosing criteria that fits the needs of each user, e.g. a scheme that causes the least losses in the network, of course without endangering smallest observed analysis criteria.

IV. STUDY CASE ON IEEE 14 BUSBAR SYSTEM

Universality test of proposed method for developing SIPS and busbar splitting schemes is given on IEEE 14 busbar system (Fig. 5). Analysis of test system performance was carried out in PSS/E. Rated power (130 MVA) of the lines connected from busbars 1 to 5 and existence of another busbar near busbar 2 were assumed.

A. *Base scenario*

Test system analysis was performed on the base scenario without any changes to the defined test system generation and consumption. Data for IEEE 14 busbar system are taken from University of Washington's test case archive [15]. Detailed analysis was performed on the part of the test system from busbars 1 to 5. There was no need to extend the analysis to other part of test system because the developed method could be applied to the specified part of the system. The base scenario is defined by the majority of generation in busbar 1 and smaller amount in busbar 2. The busbars 3, 6 and 8 are modeled with synchronous compensators that hold network's voltage security.

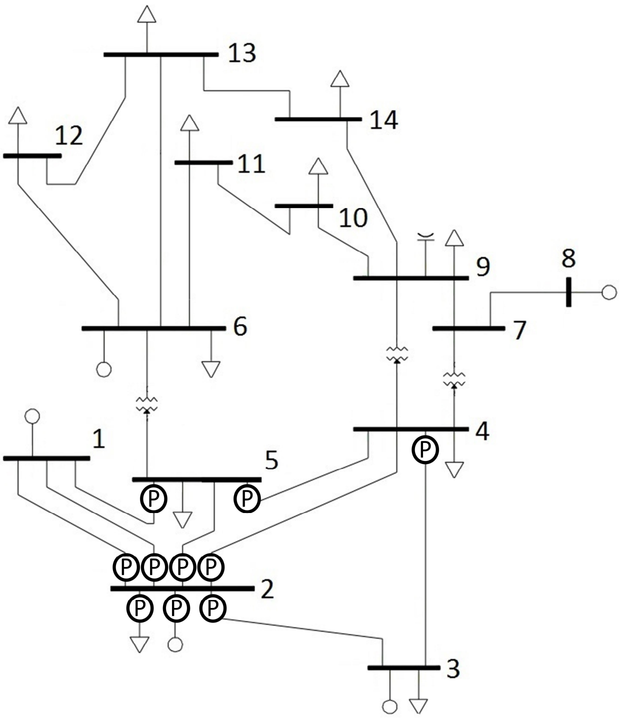

Fig. 5. *IEEE 14 busbar system with PMUs*

B. *Base scenario N-1 analysis*

N-1 security assessments of all lines connected from busbars 1 to 5 indicated the two problematic cases in which safety operation criteria are not met. Overload case (138.7 MVA) of one line between busbars 1 and 2 happens when other line between same busbars is out of operation. In the next step it is necessary to find out whether the specified overload can be mitigated by using busbar splitting scheme.

C. *Busbar splitting scheme selection*

As described in the previous chapter, it is assumed that there are two basic ways to relieve the overloaded line. It is possible to relieve line with changing topology of the network from which energy comes or into which energy goes. Since the only energy source that goes into the busbar 1 is generator itself it is not possible to relieve overloaded line by changing topology of the network from which energy comes. Busbar 2 is connecting six elements of which four lines, one generator and one load. It is necessary to check whether the separation of busbar 2 can relieve overloaded line.

It is determined that two elements, line 1-2(2) and generator, lead power to the busbar, and the other four elements, lines 2-3, 2-4, 2-5 and load, derive power from the busbar. Five possible combinations of splitting busbar 2 were assumed using combinatorial and heuristic methods. Testing all five suggested combinations indicated that only two busbar splitting options can relieve the overloaded line in the allowed limits.

D. *SIPS activity and initiation conditions preliminary proposal*

Two busbar splitting schemes for busbar 2, IEEE 14 A and B, are shown in the Table II. Both options mitigate overload of line 1-2(2). Their comparison and selection of the recommended scheme is carried out in the last chapter of the developed method.

TABLE II. SUGGESTED BUSBAR SPLITTING SCHEME ACTIONS

SIPS	SIPS IEEE 14 A
Substation	2
Busbar 2	Line 1-2(2) and 2-3; Load 1
Busbar 21	Line 2-4 and 2-5; Generator 1
SIPS	SIPS IEEE 14 B
Substation	2
Busbar 2	Line 1-2(2), 2-3 and 2-4; Generator 1
Busbar 21	Line 2-5; Load 1

Initiations of proposed busbar splitting schemes are defined with following conditions:

- synchronized phasor measurement values – line 1-2(2) overloaded, all other lines in normal boundaries,
- binary status – line 1-2(1) disconnected, all other lines connected.

Graphical representation of busbar splitting scheme initiation conditions supported by SPMT is shown in Fig. 6.

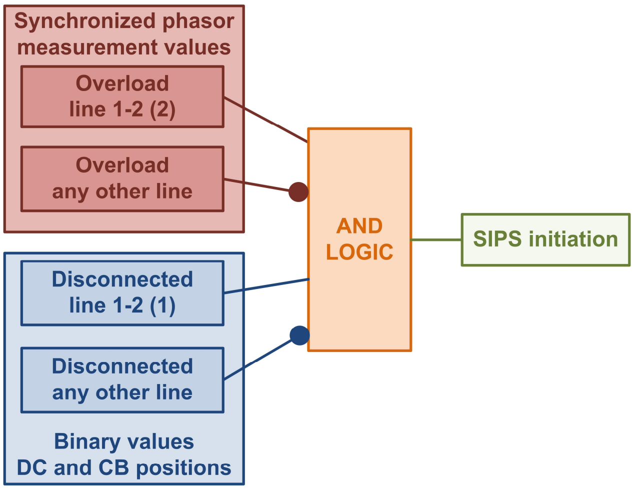

Fig. 6. *SIPS initiation conditions for IEEE 14 busbar system*

SIPS initiation conditions will largely determine the PMU placement. Other determining factors may be related to communication connectivity problems or availability of GPS. PMU placement is well researched and developed area as it appears in the initial use of SPMT. Paper [16] introduces the complete and incomplete system observability placement techniques. Incomplete observability is described with the concept of unobservability depth that directly affects the total number of required PMUs. Paper [17] introduces a critical locations method together with observability method. The critical locations method consists of determining the buses with a large number of elements or with limit voltage values that may affect the security of the system. Both papers define that SPMT application in SIPS requires PMU placement based on complete system observability. PMU placement example of the considered part of the IEEE 14 busbar system based on complete observability method is shown in Fig. 5.

E. *SIPS initiation simulation*

Simulations of each busbar splitting scheme were made within Matlab environment. Simulations confirmed full functionality and initiation accuracy of designed schemes based on the given conditions. Fig. 7 shows joint simulation of all proposed SIPS supported by SPMT for tested IEEE 14 busbar system.

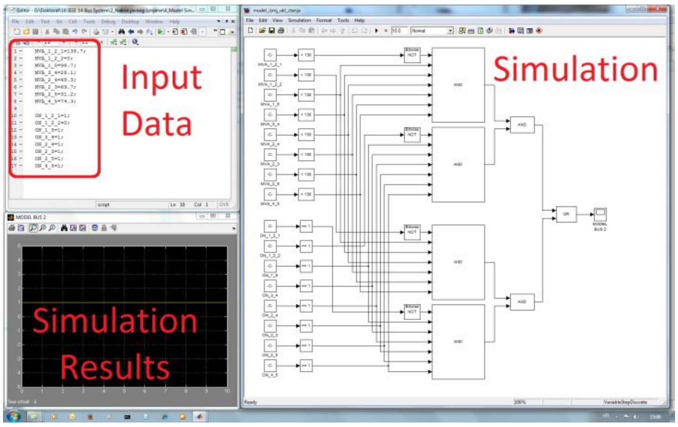

Fig. 7. *SIPS Initiation Simulation for IEEE 14 Busbar System*

F. *IEEE 14 busbar system security assessment with and without SIPS implementation*

IEEE 14 busbar system security assessment with and without SIPS implementation consists of comparison of power flows and voltage conditions together with production, consumption, exchange and loss levels. Fig. 8 shows in red maximum transmission capacity (130 MVA) of all analyzed lines from busbars 1 to 5.

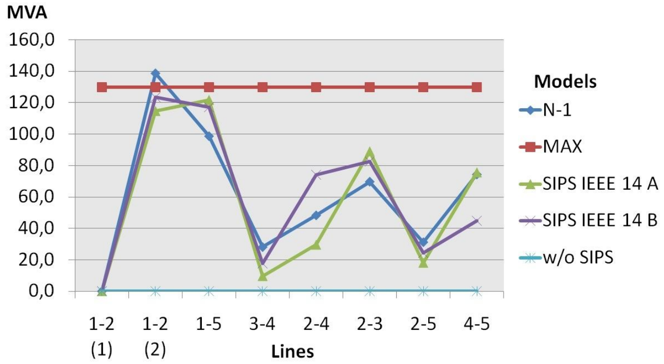

Fig. 8. *Power flow comparison – lines*

N-1 analysis of line 1-2(1) clearly shows overloading of line 1-2(2). Without use of SIPS supported by SPMT, tripping of overloaded line from local relay protection system would lead to a voltage breakdown of the observed network part and the consequent system breakdown. The same figure shows the distribution of the power flows in the case of using two proposed SIPS, IEEE 14 A and B. It is evident that using any of the proposed busbar splitting scheme of busbar 2 will bring back power flow of line 1-2(2) within allowed limits.

Fig. 9 shows relations between voltage angles of all buses in the observed part of the test system. It is evident that the usage of the proposed SIPS supported by SPMT changes voltage conditions comparing to N-1 analysis. The voltage angles between buses generally increase, but they don't cause additional problems for system security.

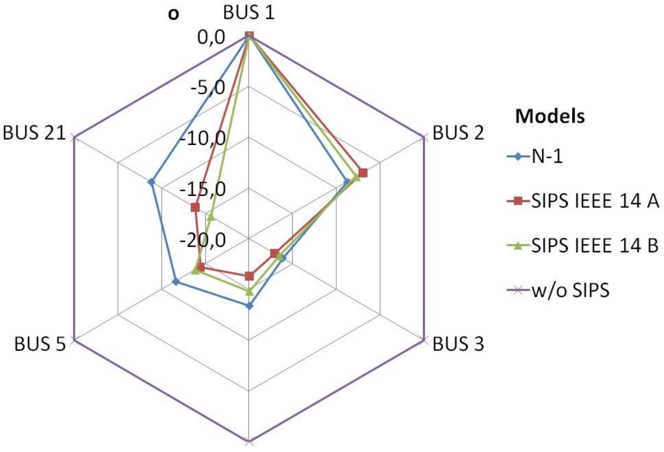

Fig. 9. *Voltage angle comparison - busbars 1-5*

Additional 1.8 MVA losses comparing to N-1 analysis are created by applying IEEE 14 A scheme, while additional 9.3 MVA losses are created by applying IEEE 14 B scheme. Fig. 10 clearly shows that the application of the IEEE 14 A scheme creates fewer losses in the observed part of the test system than using IEEE 14 B scheme.

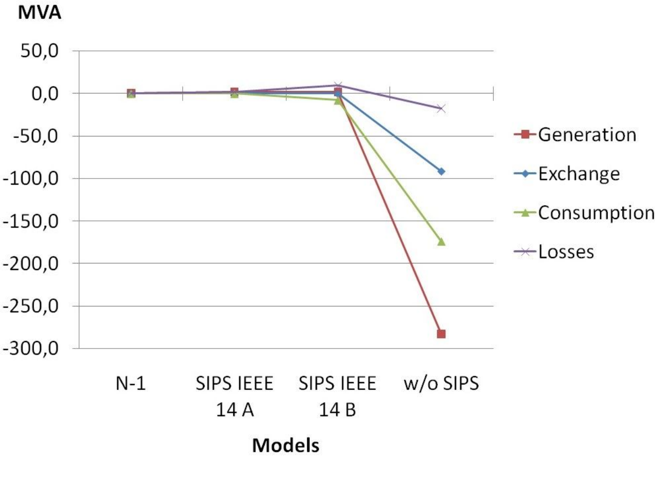

Fig. 10. *Generation, exchange, consumption and losses - difference*

Since the proposed two schemes cause satisfactory security aspects in terms of power flows and voltage conditions in observed part of the test system it is suggested to use IEEE 14 A busbar splitting scheme because it causes fewer losses.

V. CONCLUSION

This paper discusses the application of SPMT in the form of advanced control and SIPS. Overload and congestion problems of transmission networks and coordination of local relay protection systems can be solved using the SIPS supported by SPMT like it was shown in the IEEE 14 busbar system example. Future research will be directed towards the development of other types of SIPS supported by SPMT such as generation reducing or load shedding schemes.

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