Modeling of Multi-agent System for Power System Topology Verification with use of Petri Nets

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Abstract—**A correct power network topology model is essential from viewpoint of various dispatching control applications. This model is created with use of states of switching devices which are gathered in real-time. In some circumstances, there can be errors in the obtained power network connectivity model. The paper deals with the verification of the mentioned model with the use of a multi-agent system. A multi-agent system can be considered as a discrete event dynamic system. In this situation, to assess structural properties of the multi-agent system for topology verification, Petri nets can be utilized. The aim of the paper is to show rules of modeling and analyzing the considered multi-agent system with use of Petri nets.**

Keywords – power system, topology, topology verification, Petri nets

I. INTRODUCTION

A power network topology model is created with use of switching device statuses reported by SCADA. One cannot exclude existence of errors in data received from SCADA and then also errors in a power network topology model. The errors in the mentioned model lead to erroneous results of applications utilizing this model and in consequence they may be a reason of incorrect dispatcher decisions. Then, it is of great importance to have a correct power network topology model. One of the ways of coming closer to that aim is power network topology verification. The paper deals with the power network topology verification with the use of a multi-agent system [1]. Such approach, utilizing features of the agent technology [2] - [6], allows performing power network topology verification in distributed manner, what is interesting solution nowadays.

Essential problems at the stage of development of power network topology verification system are its modeling and then analyzing its characteristics. A multi-agent system can be considered as a discrete-state, event-driven system (a discrete event dynamic system). Such systems can be modeled with use of Petri nets [7] - [10]. Visualization and analytical properties of Petri nets are very valuable in this case.

The aim of the paper is to show rules of modeling and analyzing the considered multi-agent system with the use of Petri nets. Petri nets are treated as a tool for investigation of some structural properties of the multi-agent system. First in the paper, characteristics of the multi-agent system for power network topology verification are briefly described. Next, rules of creating Petri nets for the multi-agent system for power system topology verification are presented. Utilization of this tool is shown on the example of the case study of modeling and analyzing agent cooperation for power network topology verification. At the end of the paper, conclusions are given with special emphasizing possibilities of Petri nets from the viewpoint of modeling and analyzing of the considered multi-agent system.

II. THE MULTI-AGENT SYSTEM FOR POWER NETWORK TOPOLOGY VERIFICATION

A. A General Description of Topology Verification Method

The topology verification method consists of the following steps [1], [11]:

- calculation of unbalance indices for nodes and branches,
- pre-processing of the unbalance indices (pre-processing standardization),
- local classification,
- global classification.

The pre-processing standardisation allows keeping input values for RBF network in the range (0; 1]. Local classification step is aimed at assignment of input patterns to one of the classes corresponding to the correctness of modeling branches in a power system. Each local classifier corresponds to one node of a considered power network.

The global classification step produces a final decisions on correctness of modeling of power network branches. To take the final decision on correctness of modeling a selected branch the outputs of two local classifiers are considered. These classifiers are assigned to the terminal nodes of the considered branch.

Whole power network verification process can be considered as many local verification processes. A local verification process is performed by intelligent agents, which are called further as nodal intelligent agents (NAG_k , where $k \in \{1, 2, \ldots, n\}$, n – number of power network nodes), and branch intelligent agents (BAG_{kl}, where $k, l \in \{1, 2, \ldots, n\}$).

B. Nodal Agents

One nodal agent (NAG_k) is related to one node (with the number k) of the considered power network [1]. A nodal intelligent agent performs all functions of which effect is taking the local decision on existence of a topology error.

Inputs, which are required by the nodal agent NAG_k, are as follows:

- the measurement data of bus voltage V_k,
- the measurement data P_{ki}, Q_{ki} for all i from the set I_k (for all the branches k-i for which $i \in I_k$, where I_k – a set of nodes connected with the node k),
- -the nodal unbalance indices W_{Pi}, W_{Qi} for all i from the set I_k (for all the nodes neighboring to the node k).

The agent NAG_k receives:

- all the required measurement data from a measuring system,
- all the required nodal unbalance indices from the nodal agents NAG_i , $i \in I_k$ which co-operate with it.

The agent NAG_k:

- calculates the nodal unbalance indices W_{Pk}, W_{Qk} (for the node k), using the possessed measurement data of power flows,
- calculates the branch unbalance indices W_{Pki}, W_{Qki} for all the branches k-i for which $i \in I_k$, using the possessed measurement data of the voltage magnitude at the node k and the appropriate nodal unbalance indices,
- performs the local verification process, of which results (and results of the action of the agent NAG_k) are decisions regarding correctness of modeling the branches connected with the node k.

The agent NAG_k sends results of its action to the branch agents BAG_{ki}, $i \in I_k$.

C. Branch Agents

One branch intelligent agent (BAG_{kl}) is related to one branch (the branch k-l) of the considered power network [1]. The aim of each branch agent BAG_{kl} is taking final decisions regarding correctness of modeling the branch k-l. Inputs for the branch agent BAG_{kl} are decisions regarding correctness of modeling the branch k-l from the nodal agents NAG_k and NAG_l. When the branch agent BAG_{kl} knows both those decisions it takes the final decision according to assumed decision rules.

D. Cooperation of Agents

We can distinguish two variants of the co-operation among intelligent agents [1]. The classification of these variants is related to possibility of activating the process of measuring the quantities monitored by nodal agents. We distinguish *Variant* 1, when such a possibility exists and *Variant* 2, when there is no such possibility.

In the case of *Variant* 1, the topology verification can be activated by:

- a measuring system, which sends measurement data to a certain nodal agent,
- a certain nodal agent, which activates process of measuring the quantities utilized by it,
- a certain branch agent, which activates one of the nodal agents co-operating with this branch agent.

In each of the mentioned cases, apart from the initial part of operation of the agent system the further operation is the same. The first activated nodal agent activates the next nodal agents. These agents activate appropriate measuring processes, if it is required, or further nodal agents. When branch agents have already the verification decisions taken by nodal agents they produce the final verification decisions.

In the case of *Variant* 2, the topology verification can be activated only by a measuring system. When the nodal agent has already required measurement data, it starts its action. It continues its action if it has required unbalance indices from other nodal agents. If any unbalance index is not accessible the nodal agent waits until it receives this index. As in the case of *Variant* 1, when branch agents have already the verification decisions taken by nodal agents they produce the final verification decisions.

III. RULES OF CREATING PETRI NETS FOR THE MULTI-AGENT SYSTEM FOR POWER SYSTEM TOPOLOGY VERIFICATION

Petri nets are graphical and mathematical tool for describing and analyzing different real systems [7] - [10].

Petri nets are a kind of bipartite directed graph which consist of three kinds of objects: places, transitions and arcs. Arcs are directed and connect places and transitions or transitions and places.

Petri net can be formally defined as five-tuple:

$$N = (P, T, A, W, M_0), \tag{1}$$

where: P – a finite set of places; T – a finite set of transitions; $A \in (P{\times}T) \cup (T{\times}P)$, A – a set of arcs; W: $A \rightarrow \{1, 2, 3\ldots\}$, W – a weight matrix; M_0: $P \rightarrow Z_+$, M_0 – an initial marking; Z_+ - a set of nonnegative integers.

In a graph, places are represented by circles, transitions by bars (Fig 1). The directed arcs connect places and transitions or transitions and places. The places can contain tokens traveling through the net according to firing transition sequence. The transition can fire if it is enabled, i.e. all the inputs of transitions contain at least one token. After firing transition, token is removed from each input places and added to each output place.

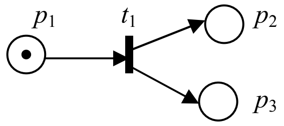

Figure 1. A simple Petri net example.

For the considered method, we can distinguish the places and transitions presented in TABLE I. and TABLE II. respectively. Arcs are defined using the places and transitions from TABLE I. and TABLE II.

TABLE I. DEFINITIONS OF PLACES FOR THE CONSIDERED METHOD.

Name	Description
p_{01}	NAG_x ready for verification
p_{02}	Unbalance indices for the node x available
p_{03}	Neighboring node unbalance indices available
p_{04}	Waiting for neighboring node unbalance indices
p_{05}	Initiation of verification
p_{06}	Final decision/Verification available
p_{07}	Local decision provided by NAG_x available

TABLE II. DEFINITIONS OF TRANSITIONS FOR THE CONSIDERED METHOD.

Name	Description
t_{01}	Request for the verification performed by NAG_x
t_{02}	Activation of the verification performed by NAG_x
t_{03}	Calculation of unbalance indices for the node x
t_{04}	Request for the neighboring node unbalance indices
t_{05}	Calculation of branch unbalance indices and performing classification by nodal classifier assigned to node x
t_{06}	Making available local decisions to the branch agents

The marking of a Petri net is defined as $M: P \to Z_+$. It can be also defined as a row matrix (a row vector) $M_j = [m_1, m_2, \dots, m_b]$, where b – number of places and $m_i = M(p_i)$, which represents the j-th state of the Petri net. M_j contains marking of all the places of a net. m_i is related with the place p_i ($p_i \in P$). m_i is a non-negative quantity, which represents the number of tokens in the place at the considered state of the Petri net. For the analyzed method $m_i \in \{0, 1\}$.

The Petri net can be represent by a reachability graph. This graph consists of nodes representing the Petri net marking and arcs connecting the nodes M_i, M_j. The arcs in the reachability graph represent transitions when firing takes the Petri net from the marking M_i to the marking M_j.

The most important properties of the Petri nets from the viewpoint of multi-agent system analysis are:

- *Reachability* – a marking M_j is said to be reachable from marking M_i if there exists a sequence of transitions that enables to take the net from the state M_i to the state M_j. The set of all possible marking that are possible from the initial marking M_0 is defined as a reachability set $R(M_0)$,
- *Liveness* – the Petri net is live for a initial marking M_0 if for any marking in the set $R(M_0)$ it is possible to fire transition. If in some state the Petri net is not live, it is said that the net has a deadlock,
- *Boundedness* – if the number of tokens in each place of the Petri net do not exceed the finite number k for any marking in $R(M_0)$ the net is bounded or k-bounded. The Petri net is structurally bounded if it is bounded for any finite initial marking M_0. The Petri net is said to be safe if it is 1-bounded.
- *Reversibility* – the Petri net is reversible, if for any marking in the set $R(M_0)$, M_0 is reachable (return to initial marking M_0).

The liveness and boundedness of the Petri net can be derived from P-invariants and T-invariants. These invariants can be obtained with a Petri net incidence matrix. The Petri net incidence matrix is defined as follows

$$a_{ij} = \begin{cases} W(t_j, p_i) & \text{iff } (t_j, p_i) \in A \\ -W(p_i, t_j) & \text{iff } (p_i, t_j) \in A \\ 0 & \text{otherwise} \end{cases}, \qquad (2)$$

where $W(p_i, t_j)$ - is the weight of the arc from p_i to t_j.

The incidence matrix $\mathbf{A}$ of a Petri net has g rows and h columns, where g, h - numbers of places and transitions, respectively.

A P-invariant of the given Petri net is a vector $\mathbf{x}$ satisfying the equation:

$$\mathbf{A}^{\mathrm{T}}\, \mathbf{x} = 0, \qquad (3)$$

and a T-invariant of the given Petri net is a vector y satisfying the equation

$$\mathbf{A}\, \mathbf{y} = 0. \qquad (4)$$

The Petri net is covered by P-invariants iff for each place p in the net, there exists a positive P-invariant vector $\mathbf{x}$ such that $\mathbf{x}(p)>0$. It is also structurally bounded if it is covered by P-invariants and the initial marking M_0 is finite.

The Petri net is covered by T-invariants iff for each transition t in the net, there exists a positive T-invariant $\mathbf{y}$ such that $\mathbf{y}(t)>0$. The Petri net that is finite is live and bounded if it is covered by T-invariants (necessary, but not sufficient condition).

IV. CASE STUDY

An agent cooperation scheme for the part of the IEEE 14-bus test system, when the power network topology verification is performed, is presented in Fig. 2. The studies were focused on the cooperation of two nodal agents assigned to the nodes 1 and 2 and branch agent assigned to the branch connecting the mentioned nodes. However, the presented considerations can be extended to the greater number of agents in easy way. Further, the *Variant* 1 of the agent cooperation, for which the measuring system sends measurement data to a certain nodal agent, is taken into account.

The aim of the case study is analysis of the Petri net for the above-described case to check that the considered system is bounded and deadlock free.

A. Modeling of the Agent System with Use of the Petri Net

The MAS-TV is considered as a discrete event system The simplified Petri net model of the part of the considered MAS-TV is presented in Fig. 3. Several interpretation can be assigned to places and transitions. Description of the assumed interpretation of places and transitions is shown in Tab. III and Tab. IV. In the presented case, places represent end of the task. The token in the place is interpreted as information on completion of the certain task. Transitions represent the activities taken by considered agents. Firing of the transition indicates that the agent performs the activity whose terminals are input and output places of the transition.

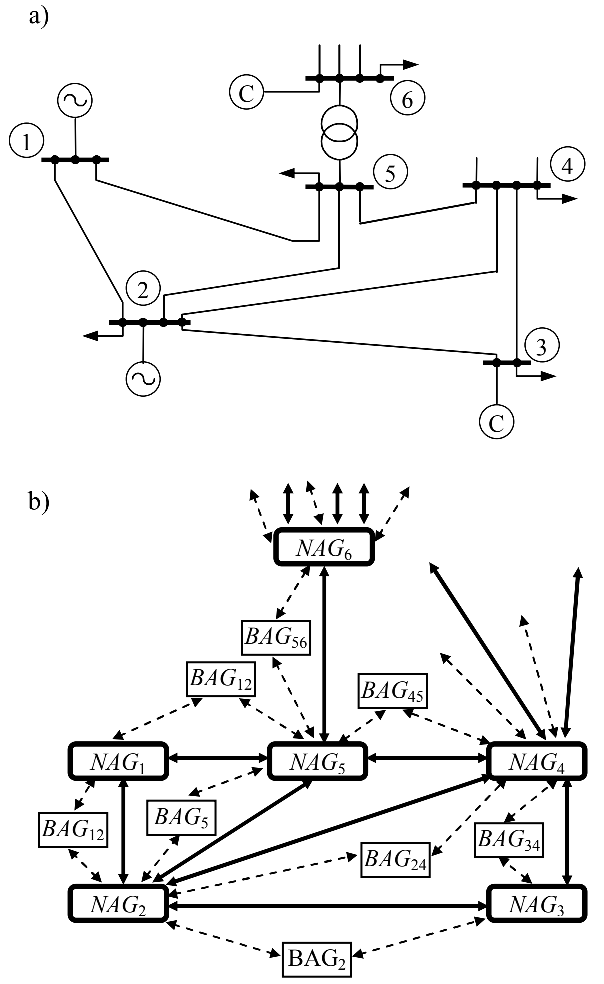

Figure 2 The part of the IEEE 14-bus test system (a) and corresponding MAS for topology verification (b).

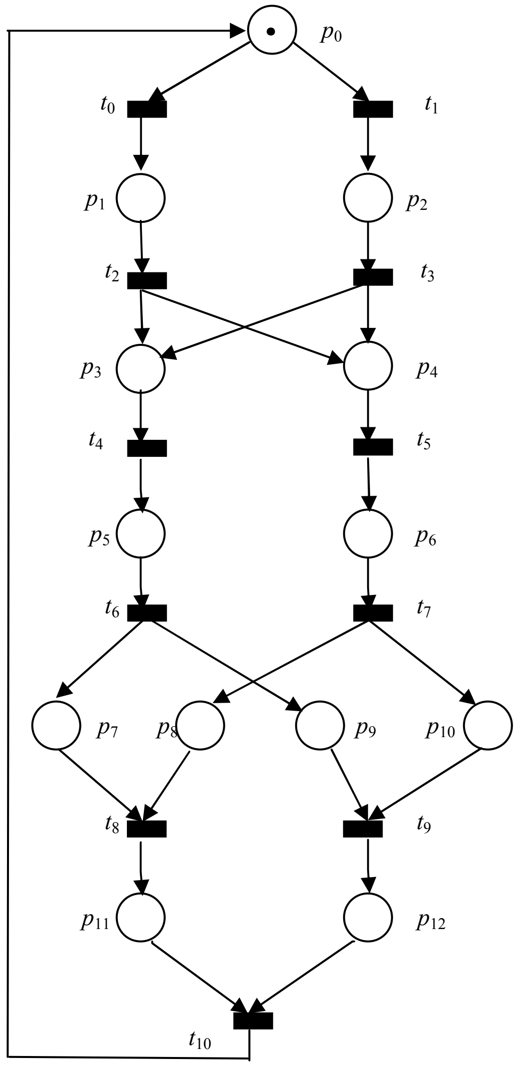

Figure 3. The Petri net model for cooperation of agents NAG_1, NAG_2 and BAG_{12}.

TABLE III. THE PLACES OF PETRI NET IN FIG. 3.

Name	Description
p_0	Final decision/Verification available
p_1 (p_2)	Initiation of the verification by NAG_1 (NAG_2)
p_3 (p_4)	NAG_1 (NAG_2) ready for verification
p_5 (p_6)	Unbalance indices for the node 1 (2) available
p_7, p_{10}	Waiting for neighboring node unbalance indices
p_8, p_9	Neighboring node unbalance indices available
p_{11}(p_{12})	Local decision provided by NAG_1 (NAG_2) available

TABLE IV. TRANSITIONS OF PETRI NET IN FIG. 3.

Name	Description
t_0 (t_1)	Request for the verification performed by NAG_x
t_2 (t_3)	Activation of the verification performed by NAG_x
t_4 (t_5)	Calculation of unbalance indices for the node x
t_6 (t_7)	Request for the neighboring node unbalance indices and performing the global topology verification
t_8 (t_9)	Calculation of unbalance indices for the branch x-y
t_{10}	Making available local decisions to the branch agents

In the case study, it is assumed that:

- The Petri net modeling the considered MAS-TV is described by $N = (P, T, A, W, M_0)$.
- $P = \{p_0, p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}, p_{11}, p_{12}\}$.
- $T = \{t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9\}$.
- $W: A \rightarrow \{1\}$.
- $M_0 = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$.

B. Reachability Graph Analysis

Analysis of liveness and boundedness can by performed by inspection of the reachability graph. Such the graph of the part of MAS-TV is presented in Fig. 4. Each node represents the marking of the Petri nets and each arc represents transition firing. Description of marking corresponding to the graph nodes is shown in Tab. V.

The resulting graph is relatively simply structured. One can observe that the reachability set $R(M_0)$ is finite and a number of tokens for every marking of places is bounded. All transitions can also be fired. It can be stated that the Petri net is bounded.

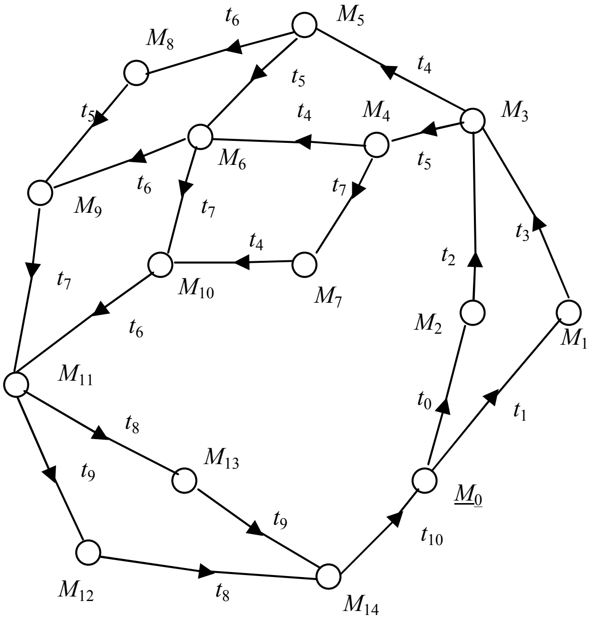

Figure 4. The reachability graph for the Petri net in Fig. 3.

There is always a fired transition regardless of the net state and all transitions are included in the graph. One can state that the Petri net is bounded and live and cooperation of agents is deadlock free.

It should be noted that for models with large numbers of places and transitions, the construction of a reachability graph seems to be impractical. In such a case, algebraic methods (implemented in computer tools) to assess graph properties are useful.

TABLE V. MARKING OF NODES OF THE REACHABILITY GRAPH IN FIG. 4.

	p_0	p_1	p_7	p_8	p_9	p_{10}	p_{11}	p_2	p_{12}	p_3	p_4	p_5	p_6
M_0	1	0	0	0	0	0	0	0	0	0	0	0	0
M_1	0	0	0	0	0	0	0	1	0	0	0	0	0
M_2	0	1	0	0	0	0	0	0	0	0	0	0	0
M_3	0	0	0	0	0	0	0	0	0	1	1	0	0
M_4	0	0	0	0	0	0	0	0	0	1	0	0	1
M_5	0	0	0	0	0	0	0	0	0	0	1	1	0
M_6	0	0	0	0	0	0	0	0	0	0	0	1	1
M_7	0	0	0	1	0	1	0	0	0	1	0	0	0
M_8	0	0	1	0	1	0	0	0	0	0	1	0	0
M_9	0	0	1	0	1	0	0	0	0	0	0	0	1
M_{10}	0	0	0	1	0	1	0	0	0	0	0	1	0
M_{11}	0	0	1	1	1	1	0	0	0	0	0	0	0
M_{12}	0	0	1	1	0	0	0	0	1	0	0	0	0
M_{13}	0	0	0	1	1	1	0	0	0	0	0	0	0

C. Structural Analysis

The incidence matrix **A** of the analyzed Petri net N is presented in Tab. VI.

TABLE VI. INCIDENCE MATRIX **A** OF PETRI NETS IN FIG. 3.

	t_0	t_1	t_7	t_{10}	t_8	t_9	t_2	t_3	t_4	t_5	t_6
P_0	-1	-1	0	1	0	0	0	0	0	0	0
P_1	1	0	0	0	0	0	-1	0	0	0	0
P_7	0	0	0	0	-1	0	0	0	0	0	1
P_8	0	0	1	0	-1	0	0	0	0	0	0
P_9	0	0	0	0	0	-1	0	0	0	0	1
P_{10}	0	0	1	0	0	-1	0	0	0	0	0
P_{11}	0	0	0	-1	1	0	0	0	0	0	0
P_2	0	1	0	0	0	0	0	-1	0	0	0
P_{12}	0	0	0	-1	0	1	0	0	0	0	0
P_3	0	0	0	0	0	0	1	1	-1	0	0
P_4	0	0	0	0	0	0	1	1	0	-1	0
P_5	0	0	0	0	0	0	0	0	1	0	-1
P_6	0	0	-1	0	0	0	0	0	0	1	0

In Tab. VI, the rows correspond to the places and the columns to the transitions, respectively.

As a result of invariant analysis four *P*-invariant vectors (Tab. VII) and two *T*-invariant vectors (Tab. VIII) were obtained.

The net *N* is covered by positive *P*-invariants iff for each place *p* there exist a positive *P*-invariant, $\mathbf{x}(p) > 0$. It can be observed by inspection of Tab. 4 that for the net *N* such the condition is satisfied. For every place in vectors $\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{x}_3$, $\mathbf{x}_4$ a positive element occurs.

The similar condition is determined for *T*-invariants and for the net *N*. For every transition in vectors $\mathbf{y}_1$, $\mathbf{y}_2$ a positive element occurs and *N* is also covered by *T*-invariants.

TABLE VII. *P*-INVARIANTS OF ASSUMED PETRI NET MODEL.

	p_0	p_1	p_7	p_8	p_9	p_{10}	p_{11}	p_2	p_{12}	p_3	p_4	p_5	p_6
$\mathbf{x}_1$	1	1	1	0	0	0	1	1	0	1	0	1	0
$\mathbf{x}_2$	1	1	0	1	0	0	1	1	0	0	1	0	1
$\mathbf{x}_3$	1	1	0	0	1	0	0	1	1	1	0	1	0
$\mathbf{x}_4$	1	1	0	0	0	1	0	1	1	0	1	0	1

TABLE VIII. *T*-INVARIANTS OF ASSUMED PETRI NET MODEL.

	t_0	t_1	t_7	t_{10}	t_8	t_9	t_2	t_3	t_4	t_5	t_6
$\mathbf{y}_1$	1	0	1	1	1	1	1	0	1	1	1
$\mathbf{y}_2$	0	1	1	1	1	1	0	1	1	1	1

A Petri net is structurally bounded if it is covered by *P*-invariants and the initial marking M_0 is finite. The net is live and bounded if it is covered by *T*-invariants (necessary condition). The considered Petri net *N* is covered by *P*- and *T*-invariants and the initial marking is finite. So, the net *N* is bounded and live.

V. CONCLUSION

Petri nets enable describing and also analyzing distributed systems. They can be used to explicitly represent static structures, information flows, satisfied conditions, and dependency relationships among transitions, such as their concurrency, sequence, and conflicting requirements. They make possible to model visualization of system behavior comprising concurrency, synchronization and sharing the resources.

Petri nets are useful tool for modeling MAS-TV. These nets can describe the behavior of agents as well as interaction among them in MAS-TV. The Petri nets allow investigating possibility of achievement of purposes for which MAS-TV is developed. Using Petri nets, one can also check occurrence of states for which assumed actions of MAS-TV cannot be performed.

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