TIMED DISCRETE-EVENT SYSTEM SUPERVISORY CONTROL FOR UNDER-LOAD TAP-CHANGING TRANSFORMERS

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Abstract: Timed discrete-event systems (TDES) have so far not been used for modelling and control of electrical power system. Since these systems have both logical and temporal behavior, we propose to use TDES to address their control problems. Under-load tap-changing transformers (ULTC) which obviously have discrete-event behavior are widely used in transmission systems to take care of instantaneous variations in the load conditions in substations. ULTC may be controlled either automatically or manually. This paper discusses the modelling and synthesis of a timed discrete-event system supervisory controller for ULTC. Different modes of operation are considered and it is shown that the specifications are controllable and the closed loop control system is non-blocking. Protective system designers in electrical power systems can use the proposed approach to verify their required temporal and logical behavior.

1 INTRODUCTION

In the last two decades, Discrete Event Systems (DES) have been studied by researchers from different fields, with respect to modeling, analysis and control. Several models have been proposed and investigated. These models can be classified as *untimed* DES models and *timed* DES models.
In an untimed model, when considering the state evolution, only the sequence of states visited is of concern. That is, we are only interested in the logical behavior of the system.
In a timed model, both logical behavior and timing information are considered. Brandin and Wonham (Brandin and Wonham, 1994) adjoin to the structure of (Ramadge and Wonham, 1987) the timing features of timed transition models (TTM)(Ostroff, 1990). The BW framework, which we use in this paper, retains the concept of maximally permissive supervision introduced in (Ramadge and Wonham, 1987) , allows the timed modelling of DES, admits subsystem composition, and admits forcing and disablement as means of control.
In the Ramadge-Wonham framework(Ramadge and Wonham, 1987), an automaton (in practice, finite) is used to model both the plant to be controlled and the specification. The RW approach successfully treats the existence and theoretical synthesis procedure of the nonblocking supervisory controller. Different synthesis methods have been developed and implemented as software TCT (Wonham, 2005) for untimed models and TTCT (Wonham, 2005) for timed models to compute controllers that are optimal in the sense that the controlled system not only satisfies the specifications but is also as permissive as possible.

Electrical power systems frequently exhibit interactions between continuous dynamics and discrete events. The power system, in its simplest representation, comprises a set of lines intersecting at nodes (buses). Energy is injected at buses by generators, and loads can be considered as negative injections. The flow of power along lines to and from buses is a phenomenon of primary interest in power system operation and control. Transformers with tap-changing facilities constitute an important means of controlling voltage throughout electrical power systems at all voltage levels. Transformers with off-load tap-changing facilities can help to maintain satisfactory voltage profiles, while under-load tap-changing transformers (ULTC) can be used to take care of daily, hourly, and minute-by-minute variations in system conditions. ULTC may be controlled either automatically or manually (Kundur, 1994).
Since emergence of DES, they have been applied to

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some problems in electrical power systems (Prosser, 1995)(Lin et al., 2004)(Afzalian and Wonham, 2006). These applications include: supervisory control, modelling and analysis, and monitoring and diagnosis of power systems. The present paper discusses the timed DES approach to design a supervisory control for ULTC. Section 2 reviews the supervisory control of timed DES. Tap-changing transformers and the logic for controlling the feeder voltage are discussed in section 3. A typical tap-changer and a set of control specifications are also modeled as some automata in section 3. The TDES models of the plant and control specification have been used to synthesize nonblocking optimal supervisors for the tap-changer in different modes of operation in section 4 as an implementation study.

2 SUPERVISORY CONTROL OF TDES

In this section, we briefly review the TDES model proposed by Brandin and Wonham (Brandin and Wonham, 1994). First, we introduce a finite automaton $\mathbf{G_{act}} = (A, \Sigma_{act}, \delta_{act}, a_0, A_m)$, called an *activity transition graph* (ATG) to describe the untimed behavior of the system. In $\mathbf{G_{act}}$, A is the finite set of *activities*, Σ_{act} is the finite set of *events*, a partial function $\delta_{act} : A \times \Sigma_{act} \longrightarrow A$ is the activity *transition* function, $a_0 \in A$ is the *initial* activity, and $A_m \subseteq A$ is the set of *marked* activities.
In order to construct a TDES model, timing information is introduced into $\mathbf{G_{act}}$. Let $\mathbb{N}$ denote the nonnegative integers. In Σ_{act}, each event σ will be equipped with a *lower time bound* $l_\sigma \in \mathbb{N}$ and an *upper time bound* $u_\sigma \in \mathbb{N} \cup \{\infty\}$ such that $l_\sigma \leq u_\sigma$. Then the set of events is decomposed into two subsets $\Sigma_{spe} = \{\sigma \in \Sigma_{act} | u_\sigma \in \mathbb{N}\}$ and $\Sigma_{rem} = \{\sigma \in \Sigma_{act} | u_\sigma = \infty\}$. The lower time bound would typically represent a delay, while an upper time bound is a hard deadline.
For each $\sigma \in \Sigma_{act}$, the timer interval T_σ is defined as $T_\sigma = \begin{cases} [0, u_\sigma] & \text{if } \sigma \in \Sigma_{spe} \\ [0, l_\sigma] & \text{if } \sigma \in \Sigma_{rem} \end{cases}$. The TDES defined by Brandin and Wonham (Brandin and Wonham, 1994) is a finite automaton $\mathbf{G} = (Q, \Sigma, \delta, q_0, Q_m)$ which can be displayed by its *timed transition graph (TTG)*. The state set Q is defined as $Q = A \times \prod\{T_\sigma | \sigma \in \Sigma_{act}\}$. A state $q \in Q$ is of the form $q = (a, \{t_\sigma | \sigma \in \Sigma_{act}\})$, where $a \in A$ and $t_\sigma \in T_\sigma$. The initial state $q_0 \in Q$ is defined as $q_0 = (a_0, \{t_{\sigma,0} | \sigma \in \Sigma_{act}\})$, where $t_{\sigma,0} = \begin{cases} u_\sigma, & \text{if } \sigma \in \Sigma_{spe} \\ l_\sigma, & \text{if } \sigma \in \Sigma_{rem} \end{cases}$. The set $Q_m \subseteq Q$ is given by a subset of $A_m \times \prod\{T_\sigma | \sigma \in \Sigma_{act}\}$. The event set Σ is defined as $\Sigma = \Sigma_{act} \cup \{tick\}$,where the additional event *tick* represents the passage of one time unit. The state transition function $\delta : Q \times \Sigma \longrightarrow Q$ is defined as follows. For any $\sigma \in \Sigma$ and any $q = (a, \{t_\tau | \tau \in \Sigma_{act}\}) \in Q, \delta(q, \sigma)$ is defined, written $\delta(q, \sigma)!$, if and only if one of the following conditions holds:

- $\sigma = tick$ and $\forall \tau \in \Sigma_{spe}; \delta_{act}(a, \tau)! \Rightarrow t_\tau > 0$
- $\sigma \in \Sigma_{spe}$ and $\delta_{act}(a, \sigma)!$ and $0 \leq t_\sigma \leq u_\sigma - l_\sigma$
- $\sigma \in \Sigma_{rem}$ and $\delta_{act}(a, \sigma)!$ and $t_\sigma = 0$

When $\delta(q, \sigma)!$, $q' = \delta(q, \sigma) = (a', \{t'_\tau | \tau \in \Sigma_{act}\})$ is defined as follows:

- if $\sigma = tick$ then $a' = a$ and for all $\tau \in \Sigma_{act}$,
  $t'_\tau := \begin{cases} t_\tau - 1, & \text{if } \delta_{act}(a, \tau)! \text{ and } t_\tau > 0 \\ t_\tau, & \text{otherwise} \end{cases}$
- if $\sigma \in \Sigma_{act}$ then $a' = \delta_{act}(a, \sigma), t'_\sigma = t_{\sigma,0}$, and for $\tau \in \Sigma_{act}$ if $\tau \neq \sigma$ then
  $t'_\tau := \begin{cases} t_\tau, & \text{if } \delta_{act}(a', \tau)! \\ t_{\tau,0}, & \text{otherwise} \end{cases}$

Let Σ^* be the set of all finite strings of elements in Σ, including the empty string ε. The function δ is extended to $\delta : Q \times \Sigma^* \rightarrow Q$ in the natural way. The *closed* behavior, the strings that are generated by $\mathbf{G}$, and *marked* behavior, the strings that are generated by $\mathbf{G}$ and lead to a marker state, of the TDES $\mathbf{G}$ are defined by $L(\mathbf{G}) = \{s \in \Sigma^* | \ \delta(q_0, s)!\}$ and $L_m(\mathbf{G}) = \{s \in \Sigma^* | \ \delta(q_0, s) \in Q_m\}$, respectively. $\mathbf{G}$ is called *nonblocking* if $\overline{L_m(\mathbf{G})} = L(\mathbf{G})$.
As in untimed supervisory control, the set Σ_{act} is partitioned into two subsets Σ_c and Σ_u of controllable and uncontrollable events. An event $\sigma \in \Sigma_{act}$ that can preempt the event *tick* is called a *forcible* event. The set of forcible events is denoted by Σ_{for}. A forcible event can be either controllable or uncontrollable. By forcing an enabled event in Σ_{for} to occur, we can disable the event *tick*. In this framework a supervisor repeatedly decides to disable or enable each event in $\Sigma_c \cup \{tick\}$.
The simplest way to visualize the behavior of a TDES $\mathbf{G}$ under supervision is first to consider the infinite reachability tree of $\mathbf{G}$ before any control is operative (Wonham, 2005). Each node of the tree corresponds to a unique string *s* of $L(\mathbf{G})$. At each node of the tree we can define the subset of *eligible* events by $Elig_{\mathbf{G}}(s) := \{\sigma \in \Sigma | \ s\sigma \in L(\mathbf{G})\}$. In order to define the notion of *controllability* we consider a language $K \subseteq L(\mathbf{G})$ and write $Elig_K(s) := \{\sigma \in \Sigma | \ s\sigma \in \bar{K})\}$. K is *controllable* with respect to $\mathbf{G}$ if, for all $s \in \bar{K}$
$Elig_K(s) \supseteq$

$$\begin{cases} Elig_{\mathbf{G}}(s) \cap (\Sigma_u \cup \{tick\}), & Elig_K(s) \cap \Sigma_{for} = \emptyset \\ Elig_{\mathbf{G}}(s) \cap \Sigma_u, & Elig_K(s) \cap \Sigma_{for} \neq \emptyset \end{cases}$$

Our control objective is, for the given plant language $L(\mathbf{G}_p)$ and the specification language $L(\mathbf{G}_s)$, to find a supervisor such that the closed loop language is, in the sense of set inclusion, the largest sublanguage of $L_m(\mathbf{G}_p) \cap L_m(\mathbf{G}_s)$ which is controllable w.r.t $\mathbf{G}_p$ and also nonblocking, written $sup\mathcal{C}(L_m(\mathbf{G}_p), L_m(\mathbf{G}_s))$.

3 TAP-CHANGING TRANSFORMERS

Transformers with tap-changing facilities constitute an important means of controlling voltage throughout electrical power systems at all voltage levels. Transformers with ULTC are widely used in transmission systems. For example, Ontario Hydro provided ULTC facilities on most 500/230 kV autotransformers and on all "area supply" transformers stepping down from 230 kV or 115 kV to 44 kV, 27.6 kV, or 13.8 kV (Kundur, 1994). Whereas many articles considered ULTC as a nonlinear element in the power system model for voltage stability studies, a model in Petri net form for tap-changer has been used in a framework of differential, switched algebraic and state-reset equations (Hiskens and Sokolowski, 2001).

3.1 Tap-Changer Control Logic

The control logic for tap-changer transformers can be found in the literature (Kundur, 1994),(Ohtsuki et al., 1991),(Otomega et al., 2003) as well as in manufacturers' catalogues (e.g. (GE, 2005))in different detail. The ULTC control logic can be summarized as follows. When the voltage is not "normal" (i.e. is outside a desired limit) then the controller changes tap ratio after a time delay to restore the voltage i.e. bring it back into its dead-band. The delay time is used to prevent unnecessary tap changes in response to transient voltage variations and to introduce the desired time delay before a tap movement. Existence of this delay in temporal behavior of the LTC motivates using TDES framework for this control problem.

3.2 TDES Modelling of the Plant

In this section the timed DES models of the plant and the control logic governing the ULTC are discussed. The models will be used later to study implementation of supervisory controller.
The block diagram of the control system for automatic changing of transformer taps is shown in Figure 1. Each component is modeled as a TDES. Then the TDES models of the plant components are composed to form the plant model.

As discussed in Section 2, we first model the system components by the corresponding ATGs for

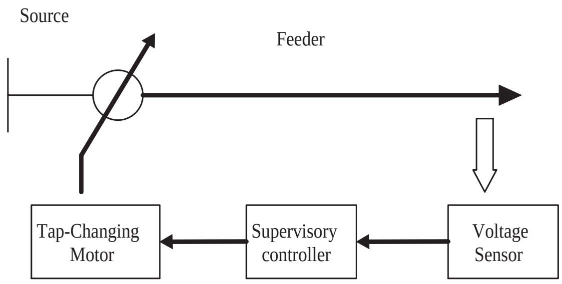

Figure 1: Block diagram of control system for automatic changing of transformer taps.

their untimed behavior. For adding time features we define the time bounds (lower and upper) for the events of the system. The plant consists of two main components:
- Voltmeter
The load voltage must be within a dead-band ($V_0 \pm ID$). where V_0 is "set point",V_l is "(measured) Load Voltage", $\triangle V = V_o - V_l$ is "Voltage Deviation" and ID is "Insensitivity Degree" which is defined as the maximum admissible variation of the voltage before originating a command to change the tap.
Voltmeter reports events associated with the load voltage using these events :
Initialize Voltmeter (ev11 , [0,inf])
Report $|\triangle V| > ID$ and $\triangle V > 0$ (ev12 , [0,inf])
Report $|\triangle V| > ID$ and $\triangle V < 0$ (ev14 , [0,inf])
Report $|\triangle V| < ID$— i.e. Voltage Recovered (ev16 , [0,inf])
Report Voltage exceeds V_{max} (ev18 , [0,inf])

- Tap Changer
The transformer tap changer controls the transformer ratio "manually" or "automatically" in order to keep the power supply voltage practically constant, independently of the load. If the tap increase (decrease) is successful, the system returns to a state and waits for another command. If the tap increase (decrease) operation fails, the controller changes to the Manual mode, and waits for another command.
It is assumed here that the tap-changer has 5 steps.
Events associated with the Tap Changer are:
Tap up command (ev31 [5, inf]),
Tap up successful (ev30 [0, inf]),
Tap up failed (ev32 [0, inf]),
Tap down command with 5s delay (ev33 [5, inf]),
Tap down command without delay (ev35 [0, inf]),
Tap down successful (ev34 [0, inf]),
Tap down failed (ev36 [0, inf]).

The ATGs for the voltmeter and tap changer are shown in Figure 2. In order to find the whole system's model, we first find the composition (analogous to synchronous product in untimed DES) of the ATGs of the system, then find the TTG of the plant by converting the ATG to TTG.

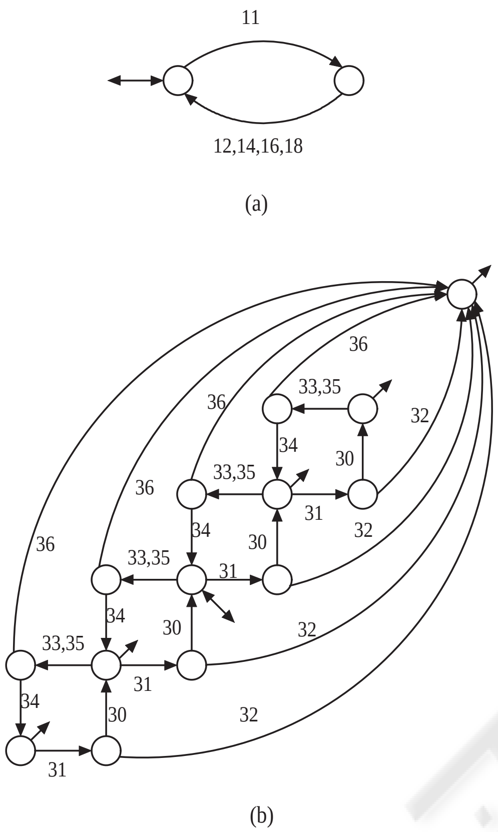

Figure 2: ATGs for (a) Voltmeter (b) Tap Changer.

3.3 TDES representation of Control Specifications

There are two modes of operation: “Automatic” and “Manual”.

1) Automatic Mode

The tap-changer works in Automatic mode according to the following logic (control specifications):

a. If the voltage deviation $|\triangle V| > ID$ and $\triangle V$ is Negative (ev14) then the timer will start and when it times out i.e. the time delay in occurrence of ev31 elapses then a “tap increase ” event (ev31) will occur and the timer will reset.

b. If the voltage deviation $|\triangle V| > ID$ and $\triangle V$ is Positive (ev12) then the timer will start and when it times out then a “tap decrease ” (ev33) will occur and the timer will reset.

c. If the voltage returns to the dead-band (ev16), because of smooth system dynamics or a tap change or some other system events, then no tap change will occur.

d. If the voltage exceeds the value set for ”Quick Lowering” (ev18), then the lowering tap command without delay (ev35) happens instantaneously.

Figure 3 shows the TDES model of the control specification in the Automatic mode. It actually implements all the above logic in a single TDES. We should mention that because in these specifications we need the events tap up/down command (31,33,35) to preempt $tick$ in some states of the specification TDES, we should define these events as “forcible” events. (Section 2)

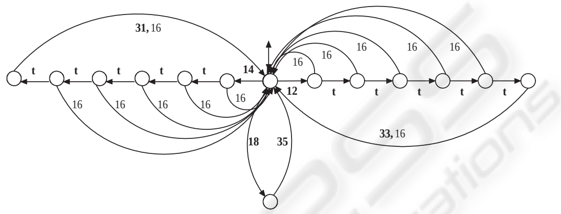

Figure 3: TTG of the control specifications in Automatic Mode.

2) Auto/Manual Mode

In this mode of operation, we need a model for the operator action to switch the modes and to override in abnormal situations. Events 41 and 43 are defined for operator actions:

Enter “Automatic” Mode (ev41, [0,inf]),

Enter “Manual” Mode (ev43, [0,inf])

The operator can force the system from Automatic to Manual mode at any time (ev43). System switches to Manual mode from Automatic mode by a “Manual” command from operator (ev43), or an abnormal situation such as, failed tap up/tap down. In manual mode the system is waiting for “Tap-up”, “Tap-down” or “Automatic” commands. On returning to Automatic mode the controller is reinitialized at state 0 of the Automatic specification (Fig. 3). A specification for the Auto/Manual mode (SPEC2) can be achieved by inserting suitable transitions after the occurrence of ev31 and ev33 and also by adding a new state as the “Manual-operation” state. The “Manual” command (ev43) takes the system from any state (*) to the Manual-operation state. Then ev41 takes this state back to the initial state. Fig. 4 shows the TDES model (TTG) for the control specification in Auto/Manual mode.

4 IMPLEMENTATION STUDY

The plant and the specification TDES models are implemented in the TTCT software. The supervisory controller has been designed for the Automatic and Auto/Manual modes of operation separately.

A. Automatic Mode

The supervisor and the control data for the ULTC in

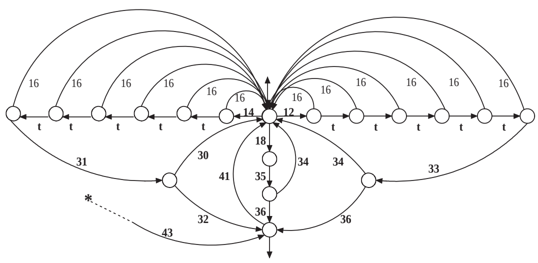

Figure 4: TTG of the control specifications in Auto/Manual Mode. The transition 43 from * represent similar transitions from all states to the “manual operation” state.

the Automatic mode are calculated using TTCT.

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SUPER1 = Supcon(PLANT1,SPEC1) (199,301)
MINSUPER1 = Minstate(SUPER1) (52,79)
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So we have found a supervisory controller for the Automatic mode of operation with 52 states and 79 transitions.

B. Auto/Manual Mode
The operator override is incorporated in the model by the control specification shown in Figure 4. Using this specification and the new plant model which is composed by the “Operator” ATG (which has one state and two transitions i.e. 41 and 43), the supervisory control is synthesized:

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SUPER2 = Supcon(PLANT2,SPEC2) (233,547)
MINSUPER2 = Minstate(SUPER2) (56,130)
PMINSUP = Project(MINSUPER2, ‘tick’) (26,53)
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As can be seen, the supervisor state-transition size is (56,130) after applying the “Minstate” operation. By projecting out *tick* from the supervisor we can display its transition structure as the *timed activity transition graph* (TATG)(Wonham, 2005). While the TATG suppresses $tick$, it does incorporate the constraints on ordering of activities induced by time bounds. The TATG of the supervisor for Auto/Manual mode is shown in Figure 5.

5 CONCLUSION

Synthesis of timed discrete-event based supervisory control for a tap-changing transformer was discussed in this work. The tap-changer components and its logical and temporal behavior have been modeled as TDES. Controllability of the specification is evaluated and supervisory controllers have been designed for two different modes of operation using the TTCT software. It is guaranteed by the synthesis procedure that the designed supervisors are optimal and nonblocking. The state size of the supervisory controller has been reduced for easier implementation. The following topics can be considered for future research work:
- Implementation of the synthesized supervisory controller on programmable logic controllers (PLC).
- Construction of a hierarchical framework for the supervisory control problem in a micro-grid electrical power system containing a tap-changer transformer and other discrete and continuous elements.

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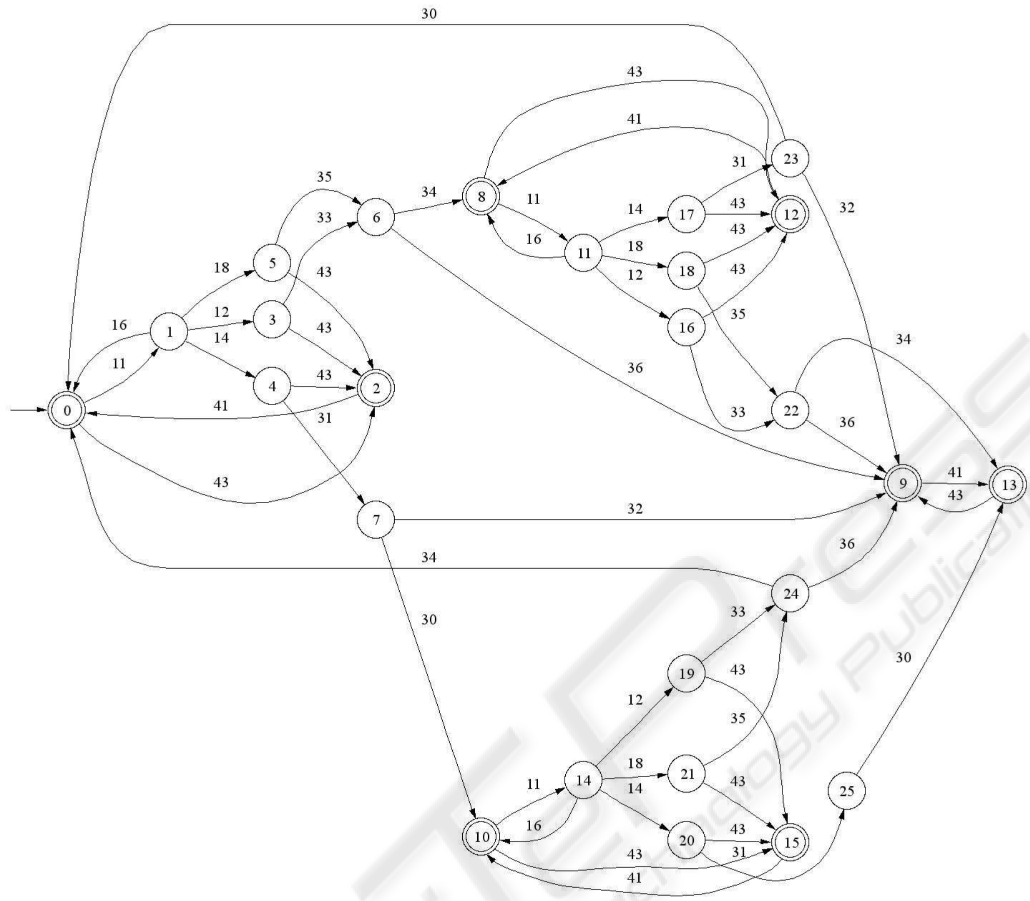

Figure 5: TATG of the supervisory controller for Auto/Manual mode of operation.