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# Supervisory Controller Design for Reactive Power Compensation

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**Abstract**

The process of reducing the phase difference between current and voltage as much as possible by balancing the reactive power is known as reactive power compensation. With reactive power compensation, over currents and voltage drops in the transmission lines are prevented and higher quality, cheaper, and more efficient energy is provided. Reactive power compensation is done by switching capacitors with proper values. In a reactive power compensation system, capacitors are switched on and off by a controller. The switching behavior of this system can be characterized as a discrete event system (DES) that has discrete states and the state evolution depends on the occurrence of asynchronous events. In this paper, the control mechanism of a reactive power compensation system is considered in the sense of DES. The system is modeled by using automata and supervisory control structures are computed. The supervisors are obtained by using the supervisory control theory (SCT). Supervisors in the form of monolithic, reduced, and modular are synthesized to correct the power factor. The computed supervisors are also integrated with the system and simulated. The total size of supervisors, ie the total number of transitions and states of each, are compared. The computed supervisors in the form of modular ones have the smallest size. According to simulation results, it is demonstrated that the power factor is successfully corrected by all of the computed supervisors. The presented study shows how to calculate controllers for reactive power compensation systems by using the supervisory control theory. Since the supervisory control theory used in the study is a formal controller computation method, the presented approach enables the computation of formal controllers for reactive power compensation systems. The use of formal methods in the synthesis of controllers offers significant benefits in terms of realization and verification.

**Keywords:** Compensation, Power Factor, Discrete Event System, Supervisory Control, Automata.

# Reaktif Güç Kompanzasyonu için Gözetimli Kontrolör Tasarımı

**Öz**

Reaktif gücün dengelenerek, akım ile gerilim arasındaki faz farkının olabildiğince azaltılması işlemi reaktif güç kompanzasyonu olarak bilinmektedir. Reaktif güç kompanzasyonu ile iletim hatlarındaki aşırı akımlar ve gerilim düşümleri engellenerek daha kaliteli, daha ucuz ve daha verimli bir enerji sağlanır. Reaktif güç kompanzasyonu uygun değerdeki kondansatörlerin anahtarlanması ile yapılır. Reaktif güç kompanzasyonu sistemlerinde kondansatörler bir kontrolör tarafından devreye alınıp çıkarılmaktadır. Bu sistemin anahtarlamalı davranışı, durum değişimi asenkron olayların oluşumuna bağlı olan, ayrık durumlara sahip bir ayrık olay sistemi (AOS) ile karakterize edilebilir. Bu çalışmada, reaktif güç kompanzasyon sistemlerinin kontrol mekanizması ayrık olaylı sistemler açısından ele alınmıştır. Sistem, otomat kullanılarak modellenmiş ve bazı gözetici kontrolör yapıları hesaplanmıştır. Gözeticiler, gözetimli kontrol teorisi kullanılarak elde edilmiştir. Güç faktörünü düzeltmek için yekpare, indirgenmiş ve modüler biçimde olan gözeticiler hesaplanmıştır. Hesaplanan gözeticiler sistemle entegre edilerek simüle de edilmiştir. Gözeticilerin toplam büyüklükleri yani her birinin geçiş ve durum sayılarının toplamı karşılaştırılmıştır. Hesaplanan gözeticilerden modüler yapıda olanın boyutu en küçüktür. Simülasyon sonuçlarına göre, güç faktörünün hesaplanan tüm gözeticiler tarafından başarılı bir şekilde düzeltildiği gösterilmiştir. Gözetimli kontrol teorisi kullanılarak reaktif güç kompanzasyonu sistemleri için denetleyicilerin nasıl hesaplanabileceği sunulan çalışma ile gösterilmiştir.

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Çalışmada kullanılan gözetimli kontrol teorisi formal (biçimsel) bir kontrolör hesaplama yöntemi olduğundan, sunulan yaklaşım reaktif güç kompanzasyon sistemleri için biçimsel denetleyicilerin hesaplanabilmesini sağlamaktadır. Denetleyicilerin sentezinde biçimsel yöntemlerin kullanılması gerçekleştirme ve doğrulama açısından önemli faydalar sunmaktadır.

**Anahtar Kelimeler:** Kompanzasyon, Güç Faktörü, Ayrık Olay Sistemi, Denetimsel Kontrol, Otomat

# 1. Introduction

In a power system, inductive loads cause the power factor to be lagging. This is very important in terms of voltage control and grid losses in power systems. Therefore, capacitors with the required size in the power system should be added automatically when needed to correct the lagging power factor. Reactive power can be controlled by switching shunt capacitors [1]. The behavior of a compensator system can be explained under the discrete event system (DES). In a DES, the system changes its states with the occurrence of physical events that are not dependent on time. Because of discrete state space and asynchronous dynamic nature, modeling of DES and design of controllers is a challenging problem. Modeling and control of many systems including manufacturing systems, robotic systems, communication systems, traffic control systems, electrical systems have been studied by different researchers in terms of DES. Although there are many modeling and computing tools in DES, two mechanisms known as Petri nets (PN) and automata are attracting more attention in academia. It is widely used in both tools in the control of DES. The supervisory control theory (SCT) that uses automata is accepted as the most general method for DES control [2, 3]. In SCT, the controller called as supervisor forces the system to act in a controlled manner by restricting the occurrence of events by using the feedback information received from the sensors about the state of the system.

In SCT, the most difficult problem encountered when computing a supervisor is the exponential increase in the number of states of the resulting model and the supervisor obtained by combining the sub-models. Some methods have been proposed to overcome this problem. Reducing the supervisor state size and computation of modular supervisors are popular ones. In classical (centralized) supervision, the whole control task is performed by a single supervisor called monolithic supervisor. In supervisor reduction [4], an algorithm that can significantly reduce supervisor size while preserving control action is used. In the modular supervisor approach [5], the DES automaton model together with a mechanism for enabling and disabling a subset of state transitions is considered. The specification can be divided into parts according to the structure of the plant. The modular supervisors are run concurrently to complete the overall supervisory task. A computer tool named as TCT [6] is widely used for computations.

Considering the works on power systems in terms of DES, some specific topics such as fault diagnosis, network reconfiguration, restoration, and reliability analysis are widely studied [7]. The switching process of capacitors in reactive power compensation systems can also be considered as a discrete system. Thus, PN modeling can be made for the control of the compensator. A discrete event systems theory application for modeling and analysis of a two-bus power transmission network can be found in Ref. [8]. This study includes the control of circuit breakers in case of failure in the transmission line. The method studied according to the simulation studies carried out in the Jarp environment enabled various failures in the power systems to be determined quickly and accurately [8]. A DES supervisory controller is designed as a dynamic flow controller in Flexible AC transmission systems (FACTS)-based power system. TCT software is successfully used to implement a supervisory controller and power flow has been carried out successfully [9]. A PN application is presented for modeling and power balance analysis of a smart grid consisting of renewable energy resources. As a result of the study, it was seen that different power sources switch-on and switch-off according to load profile and provide the energy of the load [10].

In this paper, the control mechanism of reactive power compensation systems is modeled by using automata and supervisory control structures are computed using Ramadge-Wonham's Supervisory Control Theory. The obtained supervisors that are integrated into the 2-busbar power system are verified in the simulation environment. According to the results, the power factor correction is successfully implemented by computed supervisors. It is important to use the supervisory control theory to formalize reactive power control.

In Section 2, some preliminary information on DES, Supervisory Control Theory, and the two-bus power system model is presented. DES modeling and supervisor computation are explained in Section 3. Simulation works and results for computing supervisors are provided as Section 4. Finally, conclusions are given and some future research directions are provided in Section 5.

# 2. Material and Method

The studied 3-phase power system has 2 busbars as a source and a load busbar. Because load compensation is made, compensators are also connected in parallel to the loads via controllable switches. In the conventional method, reactive power compensation is provided using a reactive power control relay and capacitors. The control relay selects which shunt capacitors are switched on or off according to the consumption of inductive reactive power per phase. In this system, capacitors are switched by a contactor that simulated with an external controllable ideal switch. The schematic diagram of the two-bus system is depicted in Fig. 1. The controller is synthesized using SCT. The control process was carried out according to the present reactive power value calculated from the current and voltage values measured from the load busbar and therefore the power factor of the system. The aim here is to bring the reactive power value in the system to zero and the power factor to 1 after compensation. Simulation studies were done in Matlab-Simulink as schematic and software.
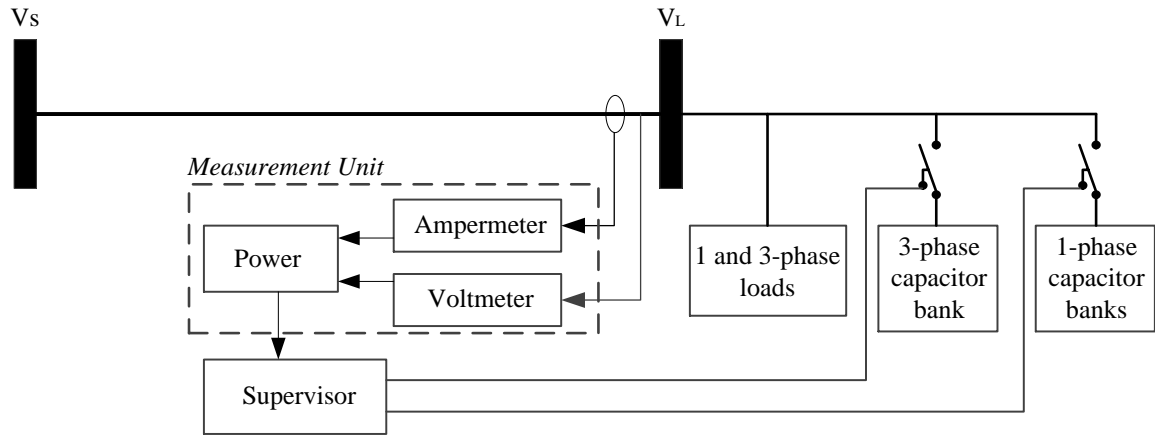
**Figure 1.** Studied two-bus power system

## 2.1. DES Modeling and Supervisory Control Theory

In supervisory control theory (SCT), the controller (supervisor) is computed to enforce some control laws named as specifications for DES. SCT uses formal languages and automat concepts for modelling and computation [2]. SCT that is known as Ramadge-Wonham (RW) method, is a well-established theory and readers can find detailed information in fundamental textbooks [2, 3]. This section only reviews some basic concepts and notation. In the method, the behavior of a plant is modeled by an automaton;

$$G = (Q, \Sigma, \delta, q0, Qm) \tag{1}$$

where Q is the finite state set; $\Sigma$ is the finite event set. $\Sigma$ is also called an alphabet in terms of language. $\delta: Q \times \Sigma \rightarrow Q$ is the transition function; $q0 \in Q$ is the initial state; $Qm \subseteq Q$ is the set of marker states. A marker state is a state that indicates the finishing of a task or an operation. The system events (alphabet $\Sigma$) are divided into two groups as $\Sigma = \Sigma c \cup \Sigma u$ where $\Sigma c$ is the set of controllable events that can be enforced to stop or start and $\Sigma u$ is the set of uncontrollable events that cannot be enforced by a controller. In DES, a physical system or a process is usually modeled as plant in the form of automaton. The behavior of the system is characterized by all possible event occurrence sequences of automaton. The automaton model of complex systems can be obtained by using the synchronous product operation.

In SCT, the controlled behavior of system can be defined by using text-based control specifications. Automata are used to model specifications. The generated language by this automaton restricts the plant to behave under control. A specification is usually the synchronous product of many smaller specifications in the form of automata. The controller called supervisor is computed based on automata models of plants and specifications. The supervisor forces the plant to comply with the specification by disabling or enabling certain controllable events that are originally able to occur in the plant. A supervisor can also be modeled by an automaton, which includes all possible event occurrence sequences in the controlled plant. A software package TCT is used for the required computations. In TCT, integer numbers are used as labels for events and states. Note that odd (respectively, even) integers are used for controllable (respectively, uncontrollable) events in the TCT software. In automata models, states can be visualized by using a circle and transitions can be visualized by a labeled arrow. A double circle is used to indicate the marker state.

## 2.2. Two-Bus Power System Model

The reactive power compensator given in Fig. 1 consists of a measurement unit, capacitor banks, and contactors. The reactive power for each phase is calculated by the control relay continuously from the load side via current and voltage measurements. In this method, the compensation is applied when the measured reactive power is 90% of the capacitor value for each phase. The system has both 1-phase and 3-phase ohmic-inductive static loads. Thus, both symmetrical and asymmetrical loading options are examined. The power values and timings of the loads are given in Table 1. First, the uncompensated system is examined. Then, depending on the load change, the necessary capacitor banks are switched by the automata-based supervisor.

*Table 1. The Load Parameters*

| Number | Power | Phase | Timing |
|--------|-------|-------|--------|
| 1 | 50 kW | 3 | 0-3.5 s |
| 2 | 30 kVAr (ind) | 3 | 2-3 s |
| 3 | 7.5 kVAr (ind) | 1 | 0.5-2.5 s |
| 4 | 7.5 kVAr (ind) | 1 | 1-2.5 s |
| 5 | 7.5 kVAr (ind) | 1 | 1.5-2.5 s |

# 3. Supervisory Control Design for Reactive Power Compensation

The DES models for plant components and the control logic for power factor correction are presented in this section.

## 3.1. DES Modeling of Plant

The reactive power compensation control system consists of a measurement unit and some switches that are used to connect capacitor bank to the system as shown in Fig. 1. The measurement unit and switches are modeled as DES and then models are synchronized to obtain the whole plant model.

*Measurement Unit:* This unit measures the current and voltage of phases and compute the reactive power. According to computed values, reports the following situations.

- Report reactive power of phase A is greater than a predefined upper limit (e10)
- Report reactive power of phase A is less than or equal to a predefined lower limit (e12)
- Report reactive power of phase B is greater than a predefined upper limit (e20)
- Report reactive power of phase B is less than or equal to a predefined lower limit (e22)
- Report reactive power of phase C is greater than a predefined upper limit (e30)
- Report reactive power of phase C is less than or equal to a predefined lower limit (e32)
- Report reactive power of each phase is greater than an upper limit and still, capacitive power required (e40)
- Report reactive power of each phase is less than or equal to the lower limit and capacitive power not required (e42)

By using these events, we can obtain the automaton models for each case as shown in Fig. 2. Each one of the models has two states (labeled with 0 and 1) and two transitions. The synchronous product of these models gives the DES model of the measurement unit. The DES model belongs to the measurement unit has 16 states and 64 transitions as shown in Fig. 3. The required TCT operations are shown in the following.

PFA = Create(PFA,[mark 0],[tran [0,10,1],[1,12,0]]) (2,2)
PFB = Create(PFB,[mark 0],[tran [0,20,1],[1,22,0]]) (2,2)
PFC = Create(PFC,[mark 0],[tran [0,30,1],[1,32,0]]) (2,2)
PFABC = Create(PFABC,[mark 0],[tran [0,40,1],[1,42,0]]) (2,2)
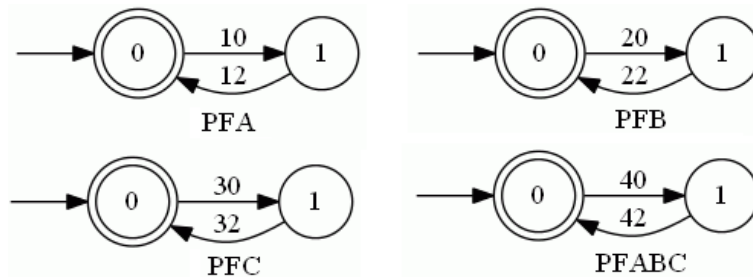PF = Sync(PFA,PFB,PFC,PFABC) (16,64) Blocked_events = None



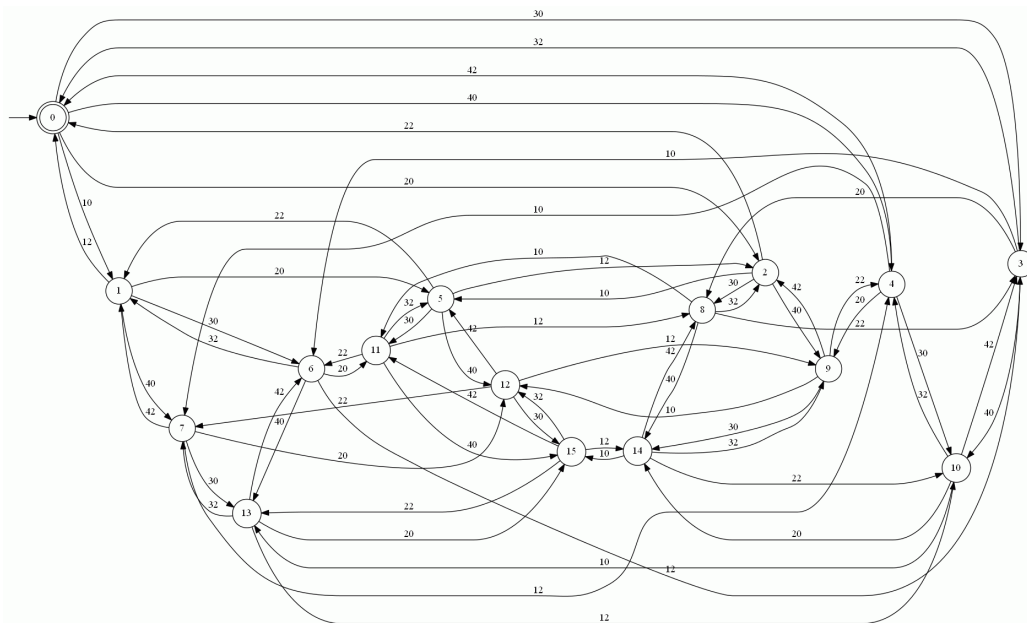**Figure 2.** Submodels for measurement unit



**Figure 3.** DES model of measurement unit

*Switches:* There are four switches in the system to connect capacitors to systems. Switches are labeled with SWA, SWB, and SWC that are connected to phase A, B, and C, respectively. A three-phase switch that is labeled with SWABC is used to connect a capacitor bank

to all phases. Each one of the switches can be controlled by using its external input. The automaton model of each switch are depicted in Fig. 4. Events and used labels are as follows,

- On command for the switch SWA (e11)
- Off command for the switch SWA (e13)
- On command for the switch SWB (e21)
- Off command for the switch SWB (e23)
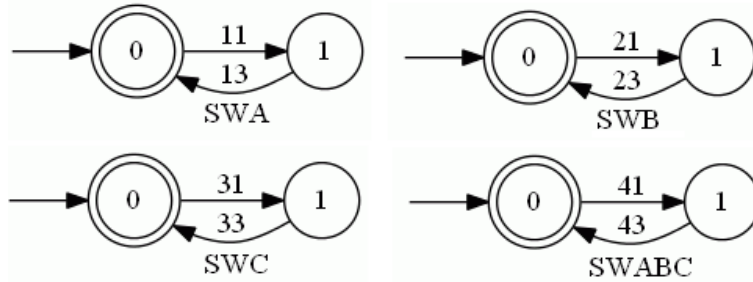- On command for the switch SWC (e31)
- Off command for the switch SWC (e33)
- On command for the switch SWABC (e41)
- Off command for the switch SWABC (e43)



**Figure 4.** Automata models of switches

To create these models in TCT, the following operation are done.

SWA = Create(SWA,[mark 0],[tran [0,11,1],[1,13,0]])  (2,2)
SWB = Create(SWB,[mark 0],[tran [0,21,1],[1,23,0]])  (2,2)
SWC = Create(SWC,[mark 0],[tran [0,31,1],[1,33,0]])  (2,2)
SWABC = Create(SWABC,[mark 0],[tran [0,41,1],[1,43,0]])  (2,2)
SW = Sync(SWA, SWB, SWC, SWABC)  (16,64)  Blocked_events = None

We can obtain the DES model of the plant by synchronization of PF and SW models as follows. The PLANT model has 256 states and 2048 transition. The schematic of PLANT model is not presented here, because the model is very huge and there is limited space.

PLANT = Sync(PF, SW)  (256,2048)  Blocked_events = None

## 3.2. Control Specifications

The conditional control of reactive power compensation can be carried out by defining appropriate specifications. In this study, the following control specifications are considered.

*Spec 1:* For any phase, if the value of inductive reactive power is greater than a predefined upper limit (90% of the capacitor's reactive power), the capacitors should be switched on. They remain on until the value of inductive reactive power is less than or equal to a predefined lower limit (20% of the capacitor's reactive power)

*Spec 2:* While individual capacitors for each phase compensate single-phase inductive loads, a 3-phase capacitor block should be switched on when a 3-phase inductive load is activated.

According to the first control specification, each one of the single-phase switches that connect the capacitor bank to the load bus individually, switches on when the inductive reactive power is greater than the critical value. The switch remains on until the reactive power value goes down to a lower limit. This specification can be partially modeled by considering each one of the switches as shown in Fig. 5. As it can be seen from the figure, specifications parts are named SP1, SP2, and SP3 for switch A, B, and C respectively. For a specification part, there are two states 0 and 1. The initial and marker state is labeled by 0. Let consider SP1 as an example. Initially, the automaton is in state 0. In this state, the switch is off. By the occurrence of event 10 namely the reactive power of phase A is greater than a predefined upper limit, the automaton changes its state from 0 to 1. In the state labeled by 1, the switch is on state. The automaton changes its states from 1 to 0, by the occurrence of event 12. A selfloop added to state 0 (respectively state 1) labeled with 13 (respectively labeled with 11) to enforce on (respectively off) the switch.
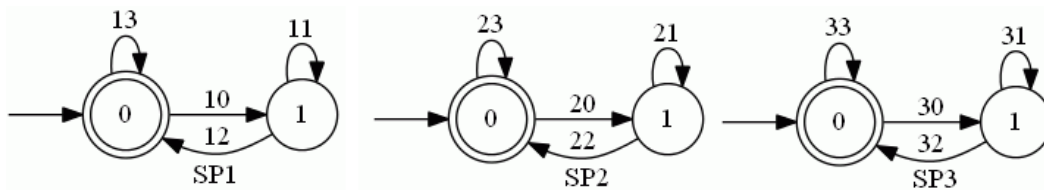


**Figure 5.** Automaton models for the first control specification

In the considered system, there are three single-phase contactors to switch individual capacitors, and also there is a 3-phase contactor to switch a 3-phase capacitor bank. According to the second control specification, if the required capacitive power is still less than the

predefined limit, the three-phase switch SWABC should be switched on. The related events (labeled 40 and 42) are provided by measurement unit to determine reactive power of each phase is greater or less than limits and capacitive power is required or not. The automaton model of this control specification is similar to other specifications part and is presented in Fig. 6. The model is named as SP4.
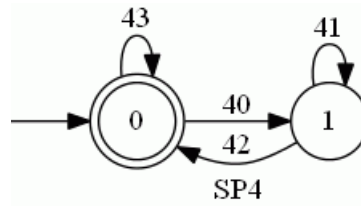


**Figure 6.** Automaton model for the second control specification

The following TCT procedures are carried out for defining all specifications:

SP1 = Create(SP1,[mark 0],[tran [0,10,1],[0,13,0],[1,11,1],[1,12,0]]) (2, 4)
SP2 = Create(SP2,[mark 0],[tran [0,20,1],[0,23,0],[1,21,1],[1,22,0]]) (2, 4)
SP3 = Create(SP3,[mark 0],[tran [0,30,1],[0,33,0],[1,31,1],[1,32,0]]) (2, 4)
SP4 = Create(SP4,[mark 0],[tran [0,40,1],[0,43,0],[1,41,1],[1,42,0]]) (4, 4)

## 3.3. Supervisor Design

According to Ramadge-Wonham method, by using the automaton model of plant and control specification the supervisor can be easily computed by using TCT tool as follows:

SPEC = Sync(SP1,SP2,SP3,SP4) (16,128) Blocked_events = None
SUP = Supcon(PLANT,SPEC) (256,1536)
CDAT = Condat(PLANT,SUP) Controllable.

This monolithic supervisor has 256 states and 1536 transitions. The TCT tool has an opportunity to reduce state size. We can apply this operation as follows:

REDSUP = Supreduce(PLANT,SUP,CDAT) (16,192;slb=16)
REDCDAT = Condat(PLANT,REDSUP) Controllable.

The result supervisor REDSUP has 16 states and 192 transitions. The state size is low but, there is still a huge number of transitions. In the realization step, the high number of states and passes in the models causes many problems such as high memory usage, the complexity of the code. As mentioned above sections, the best solution is to design a modular supervisor. We can design a modular supervisor by computing a simple supervisor for anyone of the specification part as follows:

PL1 = Sync(PFA,SWA) (4,8) Blocked_events = None
PL2 = Sync(PFB,SWB) (4,8) Blocked_events = None
PL3 = Sync(PFC,SWC) (4,8) Blocked_events = None
PL4 = Sync(PFABC,SWABC) (4,8) Blocked_events = None

SUP1 = Supcon(PL1,SP1) (4,6)
SUP2 = Supcon(PL2,SP2) (4,6)
SUP3 = Supcon(PL3,SP3) (4,6)
SUP4 = Supcon(PL4,SP4) (4,6)

The schematic of modular supervisor SUP1, SUP2, SUP3, and SUP4 are presented in Fig. 7. We should test that these computed modular supervisors have the same behavior as monolithic ones and we also should test that these modular supervisors have the property of non-conflicting with each other. We can do this as follows:

TEST = Sync(SUP1,SUP2,SUP3,SUP4) (256,1536) Blocked_events = None
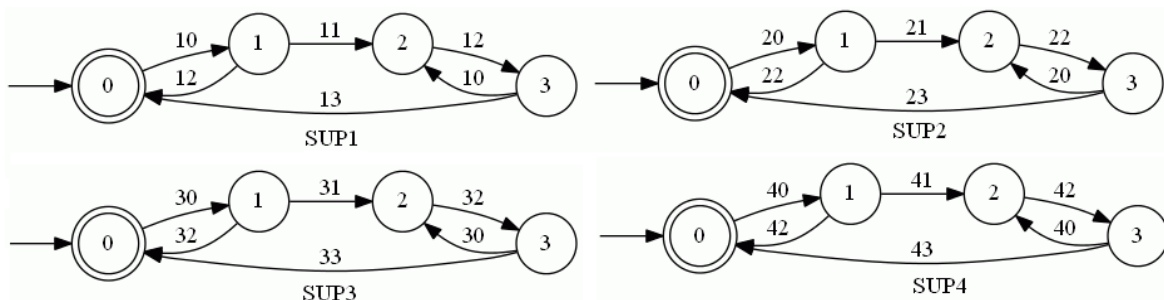
true = Isomorph(SUP,TEST;identity)



**Figure 7.** Automaton models of modular supervisor SUP1, SUP2, SUP3, and SUP4

In this test, the automaton model (TEST) that is the synchronous product of modular supervisor (SUP1, SUP2, SUP3, and SUP4) is compared with the monolithic supervisor (SUP). The result (true) shows that TEST and SUP are isomorphic under state correspondence. This means they have the same behavior.

The non-conflicting property of the modular supervisor's pair is tested as follows.

*true = Nonconflict(SUP1,SUP2)*
*true = Nonconflict(SUP1,SUP3)*
*true = Nonconflict(SUP1,SUP4)*
*true = Nonconflict(SUP2,SUP3)*
*true = Nonconflict(SUP2,SUP4)*
*true = Nonconflict(SUP3,SUP4)*

As a comparison, the number of states, transition, and total size of computed monolithic, reduced, and modular supervisors are tabulated in the following Table 2. As can be seen from the table, the modular approach gives the best solution that has a minimum size.

*Table 2. Comparison of Supervisors Size*

| Type of Supervisor | Number of states | Number of transitions | Total size |
|---|---|---|---|
| Monolithic | 256 | 1536 | 1792 |
| Reduced | 16 | 192 | 208 |
| Modular | 16 | 24 | 40 |

# 4. Results and Discussion

## 4.1. System without Compensation

The load consists of 50 kW active power at the initial condition. A step that consists of 7.5 kVAr inductive reactive power is applied at t=0.5s for phase A. Similarly, a step load that 7.5 kVAr inductive reactive power is applied for phase B and phase C at t=1s and t=1.5s, respectively. At t=2s, a step load that 30 kVAr three-phase inductive reactive power is applied to the system. The variation of the reactive power and power factor of the load without compensation is shown in Fig. 8. The power factor obtained according to the power values in Fig. 8 varies between 0.69 and 1.
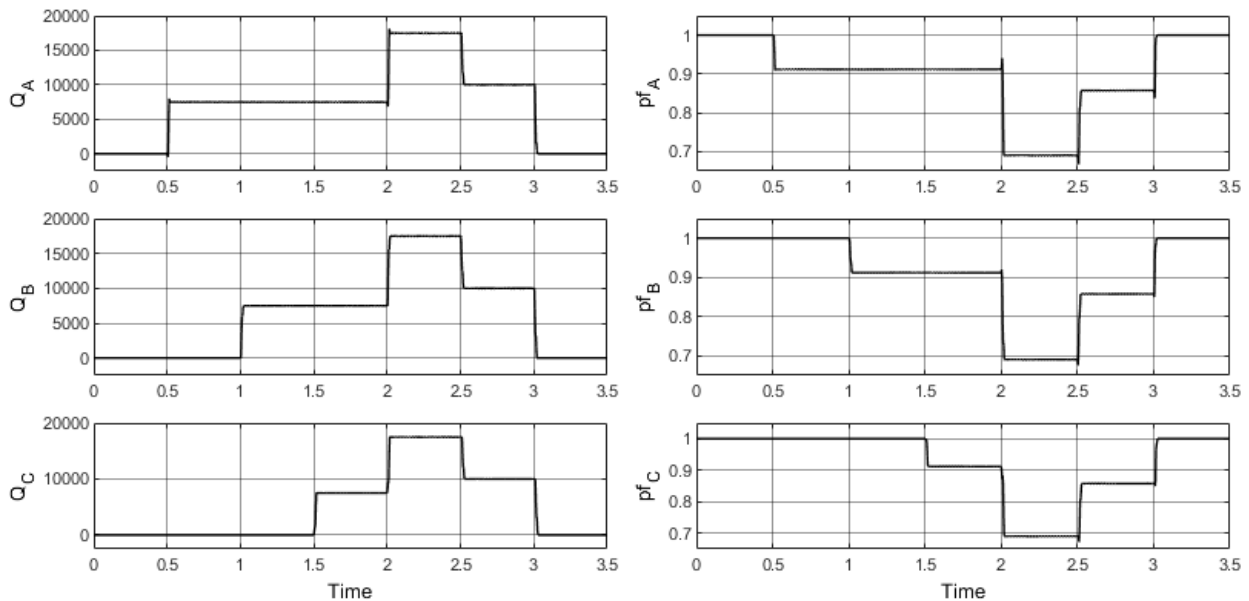


**Figure 8.** Reactive power and power factor measured in an uncompensated system

## 4.2. System with Compensation

The variation of the reactive power and power factor of the load with automata-based compensation is shown in Fig. 9. The target power factor of the load after compensation is almost equal to 1 due to using the inductive reactive load values equal to the shunt capacitor values in this study. The reactive power is peak to 6840 VAr instantaneously, when the capacitor is switched on for phase A. Also, the reactive powers are peak to 6785 VAr and 6807 VAr instantaneously when the capacitor is switched on for phase B and phase C, respectively. The reactive power is peak to 10072 VAr, 9580 VAr, and 8355 VAr when the three-phase shunt capacitor is switched on for phases A, B, and C, respectively. These values are instantaneous and can be tolerated by the system. Hence, the power factor of the load reduces transiently when shunt capacitors are switched on and off. Also, the current waveforms of the capacitors are depicted in Fig. 10. It can be seen in the figure, the switching of the capacitors have according to the need to compensate which phase.
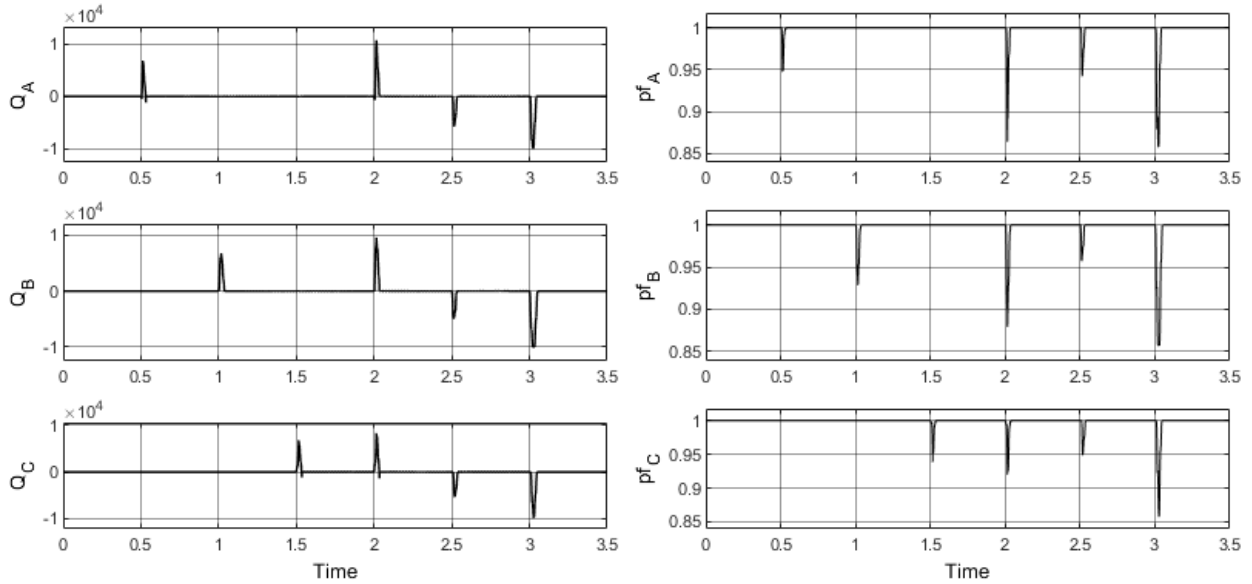
**Figure 9.** Reactive power and power factor measured in a compensated system
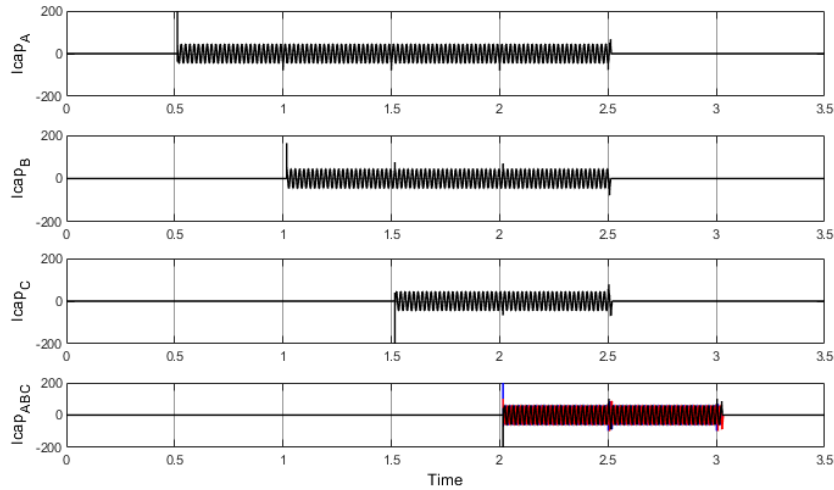


**Figure 10.** The current waveforms of capacitors

According to the presented results, reactive power compensation, which is the most basic application of power systems, has been successfully implemented with the automata method within the scope of DES. Thus, it has been shown that the operation of the conventional reactive power control relay can be formalized. Besides, the proposed method worked stably even in the case of imbalances that may occur in phases. However, as the structure of the system becomes more complex, the controller naturally becomes more complex. It can be said that the proposed control method is particularly suitable for group compensation systems.

# 5. Conclusions and Recommendations

In this work, reactive power compensation is investigated in the view of the discrete event system and supervisory control theory. Systems dynamics are modeled as automata and supervisors are computed based on monolithic, reduced, and modular approaches. It is seen that the best solution for this problem is a modular approach compared by the others in the sense of state and event numbers. Computed modular supervisors are implemented and simulated. The target power factor and reactive power values of the load are achieved by using supervisory control after compensation. In addition to the 3-phase load variation in the power system, the unbalanced load variation that occurs at different times in each phase is also taken into account. Thus, it has been seen that the proposed controller works properly not only in balanced systems but also in an unbalanced system. In the paper, a formal method based approach used to design a controller for reactive power compensation. It is possible to design scalable controllers for large-scale systems with the use of formal design methods. Besides, verification and validation of formally designed controllers can be easily done.

# References

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