ACTIVE NETWORKS

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Summary

In today's power systems it is no longer possible to talk about active and passive elements and networks using "classical" definitions. Modern power electronic devices have made it possible to manipulate voltage and current values in such a way that their effect resembles voltage or current sources. The behavior of power electronics devices often cannot be assumed constant, whether modeled as part of transient studies, dynamic studies or steady state studies. The models of such devices and the complexity of these models do vary depending on the purpose of the modeling study.

Operation of a modern active power electronic system is shown on an example of voltage source inverter (VSI) based active power filter (APF). Theory and practice of the filter operation and design are based on the theory of instantaneous reactive power in three phase systems.

This chapter primarily deals with the explanation of reactive power theory and the active filter principle of operation. As an introduction, offered are definitions for classification of electric devices and circuits into passive and active.

1. Types of Electric Networks

Electric networks or circuits, which are formed by the interconnection of electrical circuit components, can be classified into various categories i.e. linear or nonlinear, lumped or distributed, time invariant or time varying, passive or active, by examining the mathematical models used in the description of their behavior.

A linear network is a circuit composed of only linear components and is mathematically defined and described by a set of linear integro-differential equations. To determine whether a network with no initial energy storage is portwise linear, two arbitrary excitations $e_1(t)$ and $e_2(t)$ can be used. If the response to the excitations $e_1(t)$ and $e_2(t)$ are $r_1(t)$ and $r_2(t)$ then the responses to excitations $K_1e_1(t)$ and $K_2e_2(t)$ in a linear network will be $K_1r_1(t)$ and $K_2r_2(t)$, where K_1 and K_2 are constant scalars. A network that does not obey this mathematical rule is called nonlinear. Similar mathematical definitions exist for other categories of electrical networks or circuits.

Sometimes it is necessary to represent parts or elements of networks by accounting for their physical size. Examples of these elements are transmission lines and cables. If these network elements are excited at one end, it may take milliseconds for the excitation signal to propagate to the other end of the line or cable. The signal will travel at the speed of light, which will depend on the media through which the signal propagates, i.e. on type of insulation. It is therefore necessary to represent these components by allowing for their physical size. Parts or elements of networks modeled in such way are called “distributed elements”. Conversely, if it is not necessary to allow for the physical size of the part or element of the network, the elements are called lumped elements. Because the modeling and behavior of distributed elements depends on their physical size, these elements have to be represented using partial differential equations. Lumped elements are represented using ordinary differential equations.

Time invariant circuits can be defined as circuits which produce the same response $r(t)$ to the same excitation $e(t)$ regardless of the time of the application of the excitation $e(t)$.

In a similar way, classification of circuits into passive and active follows from the way these circuits are mathematically modeled.

1.1 Definitions for Active and Passive Components

A passive component denotes a component that is unable to deliver more energy to an external circuit than it initially stores. The same definition can also be applied to a circuit and network. To determine whether the component is passive, the total energy absorbed by it must be greater or equal to zero, i.e.

$$w(t) = \int_{-\infty}^{t} v(t)i(t)dt \geq 0 \qquad (1)$$

In other words, a component that absorbs more energy than it delivers is passive. If the total energy delivered by the component is greater than the total absorbed energy, the component is active, i.e. the active circuit is capable of delivering energy to the outside world.

This definition effectively reduces the active circuits to those containing voltage and/or current sources. When using this definition, one has to keep in mind that the above definition is a mathematical definition and the voltage and current sources are a mathematical interpretation of the component or system behavior.

Wrongly interpreted, the Eq. (1) would suggest that it is possible to have devices that defy the Second Law of Thermodynamics which prohibits any devices with output energy greater than the input energy. This is naturally not the case since all real voltage and current sources, such as batteries, generators, photocells, etc. have losses and cannot “create” energy. Voltage and current sources and active circuits in general, are a mathematical definition of devices or systems. These mathematical definitions are used to describe their behavior as a part of an electrical system or network.

In an electrical network, a synchronous generator is represented as a voltage source and is an active element in that electrical network. Naturally, the actual synchronous generator is not capable of delivering more energy than what it receives from its prime mover, such as a turbine or a diesel engine.

In general, voltage and current sources can be “independent” or “dependent”. The independent sources will have their output the same regardless of any other parameters or values in the network.

On the other hand, the output of dependent sources will change depending on other parameters or values in the network. Very often, voltage and current sources can be voltage or current dependant. Such dependent sources are frequently used in modeling of electronic circuits and components.

By defining the active circuits using the Eq. (1), it is concluded that models of active components and circuits inevitably have to contain voltage and/or current sources. Whilst that definition suits most mathematical models there are some that do not. This is especially the case in modeling of power electronic components and systems.

For example, a Static VAr Compensator (SVC) consisting of at least one Thyristor Controlled Reactor (TCR) is often modeled as a variable admittance (or impedance). Similarly, a Series Thyristor Controlled Reactor (STCR) is modeled as variable impedance.

The behavior of such devices is obviously dynamic and active, but their mathematical model does not necessarily have to contain any voltage or current sources. Alternative mathematical equations using voltage and/or current sources can be formulated for these devices. However, this is not always the case and may not always be practical.

Since this chapter deals with power electronics and electrical power systems where such devices are used, the author believes it necessary to introduce another definition which is arguably more suitable to this field of engineering science.

1.2 Alternative Definitions

There are different ways in which a component or system behavior can be mathematically modeled, depending on what mathematical modeling technique is used and the objective of the modeling exercise.

This can be illustrated on a mathematical representation of an inductor and capacitor. Firstly, we will model a capacitor using the well known integro-differential equations and will prove that using this modeling technique, the model of a capacitor does not contain any voltage or current sources. After that, a model of a capacitor will be developed for use in a numerical calculation using trapezoidal integration rule. Such a model is used in a number of Electro Magnetic Transient Programs (EMTP) and as it is shown, has to contain voltage or current sources. The same exercise will be repeated for an inductor.

1.2.1 Modeling a Capacitor

The current through a capacitor is given by:

$$i_C(t) = C\frac{dv}{dt} \tag{2}$$

where C is the capacitor capacitance and v is the voltage across the capacitor.
In accordance with Eq. (1), the total capacitor energy is:

$$w(t) = \int_{-\infty}^{t} v(\tau)i(\tau)d\tau = \int_{-\infty}^{v} Cvdv = \frac{1}{2}Cv^2(t) \tag{3}$$

It is immediately apparent that the total energy of the capacitor will be greater than zero if the capacitance is greater than zero. Since the capacitance is dependent on the capacitor construction, it cannot be negative. Therefore, according to the Eq. (1), the capacitor is a passive element and it is mathematically modeled without any voltage or current sources. This is true when a capacitor circuit is solved using ordinary differential equations.

However, if the same circuit is to be solved numerically using trapezoidal rule of integration, the following equation for voltage (the capacitor is connected between the nodes k and m) between nodes k and m is valid:

$$e_k(t) - e_m(t) = \frac{1}{C}\int i(t)dt$$

$$e_k(t) - e_m(t) = \frac{1}{C}\int_{t-\Delta t}^{t} i_{k,m}(t)dt + e_k(t-\Delta t) - e_m(t-\Delta t) \tag{4}$$

The trapezoidal rule of integration is:

$$\int_x^{x+\Delta x} f(x)dx = \frac{\Delta x}{2}[f(x) + f(x+\Delta x)] \tag{5}$$

When applied to the Eq. (4), the trapezoidal integration rule yields:

$$i_{k,m}(t) = \frac{2C}{\Delta t}[e_k(t) - e_m(t)] + I_{k,m}(t-\Delta t) \tag{6}$$

where $i_{k,m}(t)$ represents the instantaneous value that is being calculated and $I_{k,m}(t\text{-}\Delta t)$ represents the value from the previous time step.

With the equivalent current source known from the history (previous time step):

$$I_{k,m}(t-\Delta t) = -i_{k,m}(t-\Delta t)\frac{2C}{\Delta t}[e_k(t-\Delta t) - e_m(t-\Delta t)] \tag{7}$$

It can be seen that the model of a capacitor for each step of the numerical integration consists of a resistor of the value $\frac{\Delta t}{2C}$ in parallel with the current source having the value of the branch current from the previous time step. Therefore, for each time step, the capacitor is modeled as an active circuit.

1.2.2 Modeling an Inductor

A similar exercise can be carried out for an inductor. The voltage across an inductor is given by:

$$v_L(t) = L\frac{di}{dt} \tag{8}$$

where L is the inductor inductance and i is the current through the inductor.

In accordance with Eq. (1), the total inductor energy is:

$$w(t) = \int_{-\infty}^{t} v(\tau)i(\tau)d\tau = \int_{-\infty}^{i} Lidi = \frac{1}{2}Li^2(t) \tag{9}$$

Again, it is apparent that the total energy of the inductor will be greater than zero if the inductance is greater than zero. Since the inductance cannot be negative the inductor is a passive element and it is mathematically modeled without any voltage or current sources.

If the same circuit is to be solved numerically using the trapezoidal rule of integration, the following equation for voltage (the inductor is connected between the nodes k and m) between nodes k and m is valid:

$$e_k(t) - e_m(t) = i_{k,m}(t-\Delta t) + \frac{1}{L}\int_{t-\Delta t}^{t}(e_k - e_m)dt \tag{10}$$

When applied to the Eq. (10), the trapezoidal integration rule yields:

$$i_{k,m}(t) = \frac{\Delta t}{2L}[e_k(t) - e_m(t)] + I_{k,m}(t-\Delta t) \tag{11}$$

With the equivalent current source known from the history (previous time step):

$$I_{k,m}(t-\Delta t) = i_{k,m}(t-\Delta t)\frac{\Delta t}{2L}[e_k(t-\Delta t) - e_m(t-\Delta t)] \tag{12}$$

It can be seen that the model of the inductor for each step of the numerical integration consists of a resistor of the value $\frac{2L}{\Delta t}$ in parallel with the current source of the value of the branch current from the previous time step. Therefore, when the inductor is modeled for numerical integration it is modeled as an active circuit for each time step.

1.2.3 Alternative Definition of Active Circuits

To avoid the modeling uncertainty in differentiating between active and passive circuits, the author proposes alternative definition of active circuits which is perhaps more general, but is also more suitable for application in electrical power engineering and power electronics. This new definition is not dependent on the way a component or a system is modeled.

It is worth remembering that a component, system or circuit is represented by a mathematical model, with an input vector and an output vector. Each vector consists of a number of components.

The definition of an active component is: “*Active components have the ability to affect their output vector in a way that at least one of the output vector components is independent of the input vector*.

Alternatively, the definition of an active system can be made using its mathematical model and it is: “*Active systems are mathematically described by a system of equations with at least one equation independent of the input vector*”.

The same definition can be used for components, systems, circuits and networks.

Under this definition, voltage and current sources are active components. This definition classifies electronic components, such as diodes, thyristors, transistors, etc. as active components. Electronic circuits and systems such as voltage regulators, current regulators, active filters etc. are also active circuits or systems under this definition.

This broader and more general definition of active circuits makes power electronic components and systems active systems irrespective of the way they are modeled. They will always be modeled as active circuits, whether they are modeled as sources of reactive current, variable impedances or frequency changers. The definition from Eq. (1) would make such devices active or passive depending on the way they are modeled.

1.3 Active Circuits in Power Electronics

There are a large number of power electronics systems that are active circuits. For example, the new definition classifies systems such as uncontrolled rectifiers as active systems, since they are capable of controlling their output variables independently of the rest of the circuit or network outside the system. An uncontrolled rectifier output voltage will always be a DC voltage, independent of the input voltage frequency. Therefore, the frequency of the output voltage is independent of all inputs. The output voltage ripple can be seen as an additional output superimposed on the DC output.
Emphasis will be given to systems comprising power electronic devices. Naturally, the complexity of power electronic based active systems varies, from the simple, such as single elements and rectifiers, to complex, such as active filters. In general and as per the definition, active systems known to power electronics and electrical power engineering science today can be divided according to the parameters they control.

General voltage and current sources such as batteries, generators, etc. are excluded from this discussion and are covered in literature elsewhere. Therefore, the power electronics active systems divided according to the parameter they control are:

1) Voltage Controllers – Various active transformers, phase shifters, etc.
2) Current Controllers – active filters, motor drives, etc.
3) Frequency Controllers– rectifiers, inverters, cycloconverters, etc.
4) Impedance Controllers– Static VAr compensators, Series Thyristor Controlled Reactor, etc.

Many active systems are capable of controlling more than one of these parameters. Some are even designed to control more than one parameter, such as the Unified Power Flow Controller, which in its practical application controls the busbar voltage and flow of active and reactive power in transmission lines.

In this chapter, special attention will be given to the AC systems and in particular AC active power filters. This is a very good illustration of active systems in electric power systems and power electronics. Special attention will be given to shunt active filters.

2. Active filters

As active systems, active filters have the ability to control their output independently of the grid they are connected to[1][3][9][10]. This is true only to a certain degree and for operation within the system operating limits. It cannot be expected that the active filter generates required current during abnormal conditions and system disturbances. However, in practical terms, active filters can generate almost any current waveform independently of the grid and load current and voltage.

In general, active filters are divided in accordance with the way they are connected to the electric power system. Active filters can be shunt (connected in parallel with the load they are compensating), series (connected in series with the load they are compensating) or shunt-series. Most common in use today are shunt active filters. Shunt filters are extensively used in everyday industrial applications. Series and shunt-series active filters are still at the prototype stage. Shunt active power filters work as current sources, connected in parallel with the load, compensating the harmonic currents the load generates and generating reactive power the load requires. With appropriate control strategy, active filters can reduce and even remove unbalance in the system caused by the load. The system source only needs to supply the fundamental frequency active power.

Active filters utilize voltage or current source inverters. A brief comparison of these inverters is given in Table 1.

Current source inverters	**Voltage source inverters**
Use inductor L for DC-side energy storage	Use capacitor C for DC-side energy storage
Constant current	Constant voltage
Fast accurate control	Slower control
Higher losses	More efficient
Larger and more expensive	Smaller and less expensive
More fault tolerant and more reliable	Less fault tolerant and less reliable
Simpler controls	Complexity of control system is increased
Not easily expandable in series	Easily expanded in parallel for increased rating

Table 1: Comparison of current source versus voltage source inverters (adapted from [6])

Today's most common shunt active filters use voltage source inverters (VSI) for their operation. To explain how the filter operates, it is first necessary to describe operation of the voltage source inverter when operating as active filter.

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Biographical Sketch

Davor Vujatovic received the B.Sc. Electrical Engineering in Zagreb University, Croatia. He is a Member of the IEE, the IEEE and the CIGRE and was secretary to the DRPT 2000 International Conference on Electric Utility Deregulation and Reconstructing and Power Technologies 2000 held at City University, London

From February 1996 to April 1997, he worked as Technician Engineer in Mitsubishi Electric Europe B.V. Croydon, Surrey. He is responsible for single line diagrams and schematic diagrams design and production.

From April 1997 to July 1998, he worked as Electrical Engineer in Mitsubishi Electric Europe B.V. Croydon, Surrey. He involved in several turnkey projects for substation design and installation in the Middle East and America.

From April 1997 to July 1998, he was an Electrical Engineer in the same company involved in several turnkey projects for substation design and installation in the Middle East and America.

From July 1998 to March 1999, he was a Commissioning Engineer and was responsible for testing and commissioning of the 230/115kV substation control and protection system in Puerto Rico.

From March 1999 to October 1999, he was a Senior Electrical Engineer and was responsible for electrical design of a 400/132kV substation in Dubai.

From October 1999 to March 2001, he worked as a Senior Project Electrical Engineer in Toshiba International.(Europe) Limited, West Drayton, Middlesex

He was responsible for production of related publications and data sheets in English for European and Middle Eastern markets.

From April 2001 to April 2002, he was working in London Electricity Services as Senior Design Engineer, responsible for design, delivery, testing and commissioning of Static VAr Compensators and Load Balancer for CTRL including all related plant and systems.

From April 2002 to June 2003, as a Design Manager, he was responsible for design of the entire 25-0-25kV traction power system for Channel Tunnel Rail Link (CTRL) from the concept to the final fine-tuning during commissioning stage.

Since June 2003 he is with EDF Energy (Private Networks) London/Singlewell(Kent) as an Engineering Manager. He has the full responsibility for design, delivery, testing and commissioning of the entire 25-0-25kV traction power system for Channel Tunnel Rail Link (CTRL).