

VOLTAGE /VAR CONTROL OF ELECTRIC POWER TRANSMISSION NETWORK: A REVIEW

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Abstract

This paper presents the techniques of voltage/var control in electric power system transmission network. It introduces control sources and other familiar control systems. The four significant control algorithms (hierarchical) voltage control, optimal reactive flow(OPRF), expert system and fuzzy logic for whole transmission network are explained

Keywords: Voltage/Var, Transmission network, control devices, control systems and voltage stability

1. Introduction

Power systems may experience both over-voltage and under-voltage violations that can be overcome by voltage/var control during the daily operations [1]. Variations in supply voltage are detrimental in various respects [2]. There are basically two types of voltage variations. One is of short time duration and the other is of long time duration. The former does not formally affect our traditional electrical loads such as motors, lighting and heating applications. However, it affects some complex electronic equipment and control systems which normally have to be regulated as they affect all our traditional electrical loads in an adverse manner. Every electrical appliance is designed to operate at a certain rated voltage i.e. the best performance is obtained when the rated voltage is applied.

The problems of low voltage in power system are as follows:

- i. Resistance load like electric stoves, iron, water heater, toasters etc, will take longer to heat up.
- ii. Motor loads like vacuum cleaner, washing machine, fans, refrigerators, air conditioners, etc. will result in increased slip with increased current which decreases efficiency, overheating of the motor, thereby accelerating the ultimate breakdown.
- iii. Radio receivers, television sets etc. will also have poorer quality of reception.
- iv. Output of incandescent and fluorescent lighting would have decreased lamp efficiency. A 10% decrease in voltage results in 70% normal illumination output.
- v. It affects quality control in processing industries.

The consequences of over voltage are:

- i. Insulation at the point of fault is momentarily subjected to voltage stress in excess of its dielectric strength resulting in system faults.
- ii. Harmonic voltages resulting from unbalanced currents flowing in rotating machines in which the reactances in the direct and quadrature axes are unequal leads to magnetic saturation.
- iii. It results in motor running overexcited, resulting in increased torque and possible damage to appliances.
- iv. It reduces the life expectancy of lamp and television tube.

Voltage/Var control can maintain the voltage profile within acceptable limit with reduction of transmission losses through controlling the production, absorption and flow of reactive power at all levels in the system. The interest of the academic and industry have been attracted to this problem resulting in production of many special devices and algorithms. Some countries have adopted some of these in their real power networks and achieved reasonably successful results [3].

This paper discusses various power system components which generate reactive power and or absorb reactive power and control devices for them. The four significant control algorithms (hierarchical voltage control, optimal reactive power flow (OPRF), expert system and fuzzy logic) for whole power transmission network are explained. Rigorous mathematical solution, smart artificial intelligence approaches, research projects and real applications are covered by these algorithms. The state of the art of voltage/var control is reflected.

2. Reactive Power Generation And Absorption Sources

The controllable reactive power generation and / or absorption sources include: synchronous machines, shunt capacitors shunt reactors, overhead lines, transformer, cables and loads.

Synchronous Machines: The generation or absorption of reactive power depends on the excitation. An over-excited synchronous machine operated either as generator or motor generates reactive power and acts as a shunt capacitor as viewed from the network, absorbs reactive power from the network and acts, consequently, as a shunt reactor, if viewed from the network. Synchronous generators provide the cheapest means of reactive power supply or absorption when required to supply active power also.

The present trend towards large generators in a limited numbers of stations divorced from the distribution system makes this source of reactive power generation less attractive, since it is generally undesirable to transmission lines as this produces excessive voltage drop. The reactive power required by a consumer are usually produced locally, therefore, either by static capacitors or by synchronous motors running idle and at increased excitation [4].

Shunt Reactors: The shunt reactors offer the cheapest means of reactive power absorption and these are connected in the transmission line during light load conditions.

Shunt Capacitor: The shunt capacitors offer the cheapest means of reactive power supply but these are not as flexible as synchronous condenser (Synchronous motor running at no load and over-excited).

Overhead Line: Transmission line generates reactive power in their shunt capacitance, and consume reactance power in their series inductances. The inductive reactive power vary with the current which the line carries expressed as [4].

$$\Delta Q_L = |I|^2 X_L = [I]^2 \omega L \quad (1)$$

Where ω is the supply angular frequency and L the inductance of the line. The capacitive reactive power vary with the system potential given as:

$$\Delta Q_C = \frac{|V|^2}{X_C} = [V]^2 \omega C \quad (2)$$

where c is the shunt capacitance of the line.

Transformer: Transformer always absorbs reactive power. The total reactive power absorbed by transformer is expressed as:

$$Q_T = 3 |I|^2 X_T V_{AR} \quad (3)$$

where X_T is in ohms, I is in ampere.

Cables: Cables have high capacitance than transmission lines, consequently, generate more reactive power than transmission lines. a 132kV cable produces roughly 1.356 MVAR per kilo meter and a 33kV cable 0.12MVAR per kilometer.

Loads: Loads especially motors consume reactive power made up of two components, namely, the magnetizing component and component dependent on stator and rotor leakage. In planning a network, it is desirable to access the reactive power requirements to ascertain whether the generators are able to operate at the required power factors for the extremes of load to be expected.

3. Methods Of Voltage Control

The problems of maintaining the voltage within the tolerances is complicated by the fact that the system is supplied from many sources, and it is supplying many loads at all levels of the power system consequently it is not sufficient to maintain the voltage at only one specific point in the system, on the contrary it must be maintained at many points of the power system.

Reactors, capacitors, induction regulators, transformers are traditionally switched on/off through circuit breakers on command from the operator. Advances in flexible AC transmission systems (FACTS) controllers in power systems have led to their application to improve the voltage profile of power networks since the early eighties. Reactive Power Controller (RPC) and Static Var Compensation (SVC) are the most frequently used devices. The RPC connects or disconnects capacitor stages automatically by detecting the phase divergence between the fundamentals of current and voltage. The measured divergence is compared with several segmental set phase divergence regions, capacitor contacts will be switched on or off according to it.

Compared with RPC, the SVC is more advanced electronics equipment. It can provide continuous capacitive and inductive reactive supply to the power system. The SVC typically consists of a Thyristor Controlled Reactor (TCR), a Thyristor Switched Capacitor (TSC) and AC Filters (ACF). A typical arrangement is shown in fig 1.

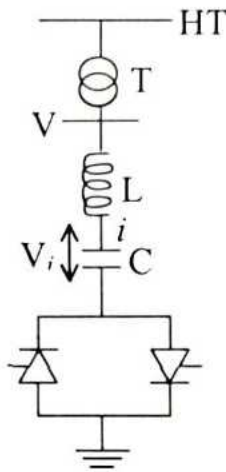


Figure 1: Equivalent SVC

Its output can vary depending on the level of generation and absorption of reactive power so as to maintain its terminal voltage at a certain level. Large financial investments are incurred in both RPC and SVC. The reactive power sources of a network must be coordinated with the aim to achieve network voltage stability.

Other methods for voltage control are explained as follows:

i. Optimal Reactive Power Flow

Similar to many other engineering problems, the complexity of the voltage/var control problem led, from the beginning, to the use of mathematical methods. It is formulated as a constrained nonlinear optimization problem called Optimal Reactive Power Flow (OPRF):

$$\min f(x, u) \quad (1)$$

subject to

$$g(x, u) = 0 \quad (2)$$

$$x_{\min} \leq x \leq x_{\max} \quad (3)$$

$$u_{\min} \leq u \leq u_{\max} \quad (4)$$

$$h_{\min} \leq h(x, u) \leq h_{\max} \quad (5)$$

Where the $f(x, u)$ represents the goal for voltage/var control and can include, for example, voltage variation around standard values and transmission losses. Constraints defined by equation (2) are the load flow equations to be satisfied at any operating point. Constraints defined by (3 - 4) are the minimum and maximum permissible control (u) (generator voltage, transformer's tap position and var compensation) and state variable (x) (bus voltage magnitude and angle). Constraints defined by (5) are the security constraints that include the minimum and maximum permissible MVAR loading limits for generators, line loading limits etc.

A popular approach is the primal – dual log barrier interior point algorithm [5]. It first transforms all inequality constraints into equalities by adding non-negative slack vectors, $s_i \geq 0$; secondly, the non-negative condition $s_i \geq 0$ are handled by incorporating them into logarithmic barrier terms, thirdly, the necessary Karush – Kuhn – Tucker (KKT) conditions of the Lagrange function of the equality constrained problem is formulated, finally, the non linear KKT system is approximated by a Newton's method. This interior point based method can deal with several thousand variables and achieve efficient convergence speed. Based on its results, the optimal reactive power control setting for current steady state can be decided. But the OPF can only reflect the steady state of power system. The high computation burden and a large number of controller movements make it less than an ideal tool for voltage/var control.

ii. Hierarchical Voltage Control

Italy is one of the pioneers who have implemented automatic voltage regulation of the synchronous generators. Its approach is based on a hierarchical control structure (figure 2) [6], which involves spatial and temporal decomposition of the whole control problem into several sub-problems.

Control Level	Tertiary	Secondary	Primary
Response Time	Around 15 minutes or longer	One minute up to a few minutes	A few seconds up to one minute
Control area	Entire network	One zone	Single or a few units

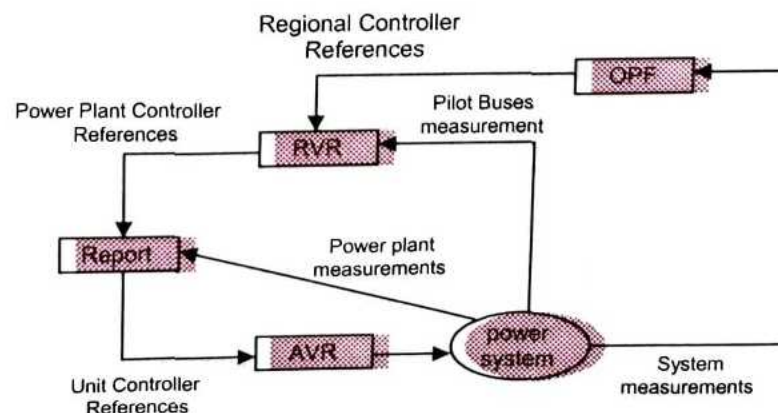


Figure 2: Hierarchical Voltage Control

The spatial decomposition follows the existing multi-level hierarchy of a power system, which divides the national network into areas around the pilot nodes. The behaviour of the other nodes' voltage for normal perturbation follows the behaviour of a pilot node's voltage in an area. The temporal decomposition is achieved by assigning a distinct response time to every level according to their complexities.

The National (Tertiary) Voltage Regulator (NVR or TVR) periodically receives (every 15min) the state of the power system. Then an Optimal Power Flow (OPF) computes the forecast optimal targets for the pilot node voltages based on current status and short-term load forecast. The set points are transmitted to the second hierarchical level that consists of the Regional Voltage Regulator (RVRs) and the Power Station Reactive Power Regulators (REPOTs). After the RVR receives the set points of its pilot nodes, it decides the reactive power level for the REPORTs control power stations to deliver their reactive power proportionally to the reactive capability limits of the control units.

This approach had been implemented in Romanina, Italy, France, Spain, Belgium and some other countries. It is also the most mature automatic voltage/var control system.

It improves the voltages to normal values in a closed loop after any contingency happened and continuously manage the reactive power generation based on the solution of OPF to keep a large enough margin for preventing voltage collapse. The transmission losses are also reduced by keeping the pilot nodes' voltages at their optimal values. This has another advantage of alleviating the operator's job and the operator can concentrate their efforts on the slow variation voltage/var profile (e.g daily peak to off-peak). But some limitations to this approach are:

- Coupling exists between some zones.
- Pilot nodes are difficult to decide.
- Too frequent control on the generators.
- Not considering the important effect of the other reactive power resources (capacitors etc.) together in real-time.
- It does not possess the capability to gain knowledge from experience.
- Analytical solutions cannot accurately reflect the nature of the stochastic power transmission system.

These disadvantages limit its wide application in real power networks.

iii. Artificial Intelligence Based Algorithms

Artificial intelligence provides possible alternatives to overcome the limitations of the classical analytical methods [7].

Tan and Michael deployed an expert system on Tasmania power network in Australia in 1995 [7]. The expert system interacts with the power system analysis software providing analysis of the network sensitivity matrix and data for the knowledge base. They approach the problem in two steps.

- Solving the AC power flow for base case to identify the weakest area and the critical contingency, then constructing the "Three tier" internal subsystem around weak area.
- The inference engine (figure 3) of the expert system employ the empirical and heuristic rules saved in knowledge base and sensitivity matrix from the network sensitivity analysis program to select the most effective control action.

The hybrid expert system's computational performance is improved significantly by reducing the size of power systems and eliminating the less effective voltage controllers. The embedded knowledge also enhances the accuracy over the classical sensitivity matrix method. But it can only perform the existing rules rigidly and had no insight to discover new knowledge.

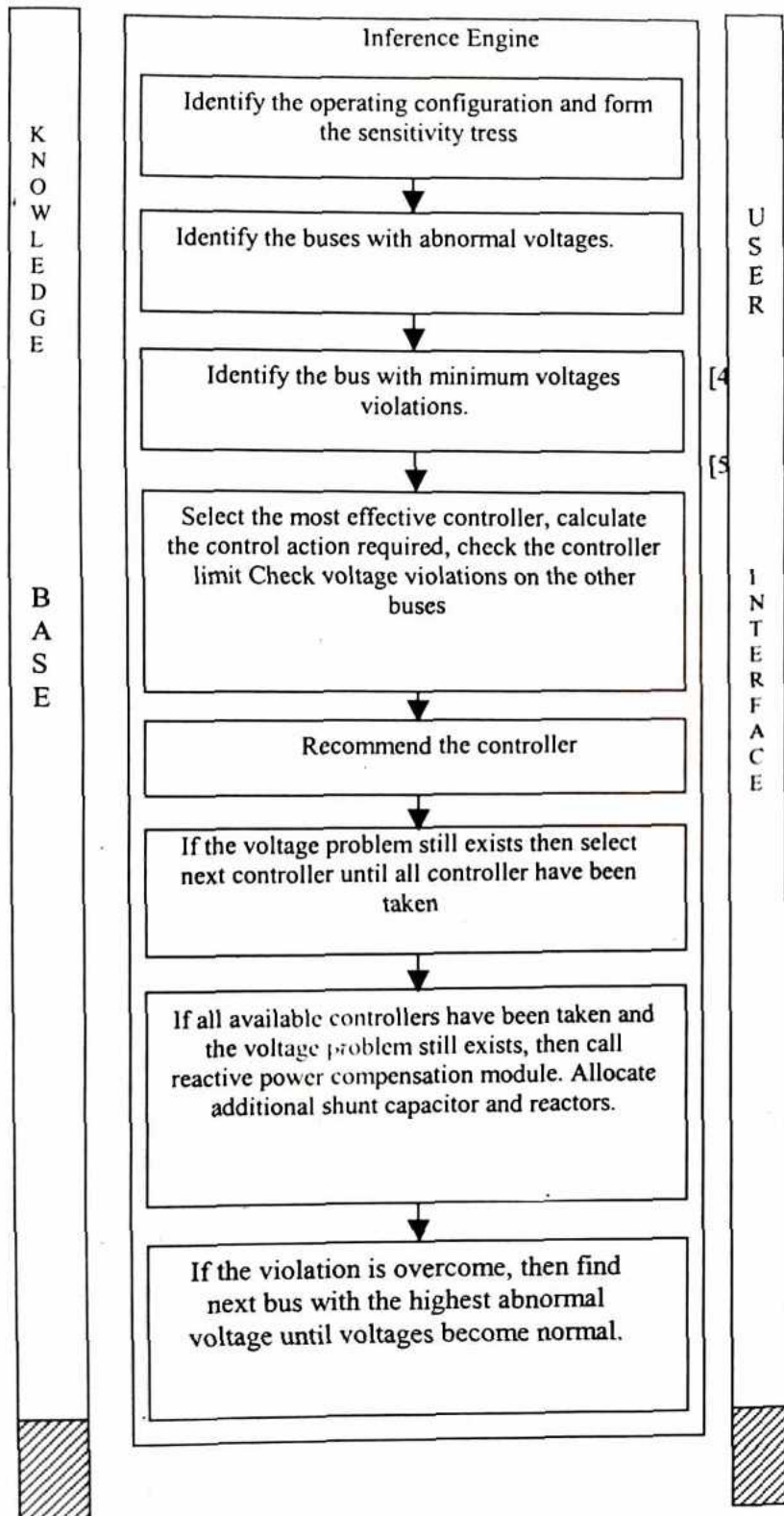
Also, it can only solve the current voltage violations and cannot deal with the dynamic stochastic nature of voltage/var control problem.

Fuzzy logic can deal with the uncertainties of real power system through fuzzy set theory. B Vankatesh and G. Sadasirm combined fuzzy logic with successive linear programming to solve voltage/var control problem [8]. After solving the base case power flow, the multiple objectives (economic and security) are formulated by a linear function with reactive power control variable. Every objective and constraint is expressed by a membership function that defines the degree of closeness to the optimum when it assumes a value. Then the objective functions are pushed as close as possible to their optimum values and the enforcement of constraints are maximized by maximizing the minimum of these membership functions. These steps are successively repeated until the improvement is small compared with the National successive linear programming more satisfactory solution is found. But it only deals with steady state power system.

4. Conclusion

Several representative techniques of voltage/var control are reviewed in this paper. Their advantages and disadvantages are analyzed. The

future challenges are how to efficiently and accurately solve the problem taking into consideration the dynamic nature of power systems.



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Figure 3: Expert System's Search Strategy.