ELECTRIC POWER TRANSMISSION OPTIMIZATION

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Abstract
In this paper, the optimization of an electric power transmission system is presented giving specific consideration on system configuration and characteristics. It is a fact that power transmission systems are meshed in configuration unlike the distribution systems that are usually configured in radials. The nature of electric power transmission networks makes it hard to manage. Thus, giving need for optimization. Transmission systems are characterized by long lines leading to; increased cost of investment, maintenance and line losses. So the problem of optimization of electric power transmission as considered in this paper is that power flow (Optimal Power Flow (OPF)) modeling considering investment cost minimization, minimization of transmission losses, optimal maintenance and maximization of power delivery, all subject to power constraints. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment such as generator real and reactive power output, bus voltages, shunt capacitors/reactors, transformer tap-setting and power flow of transmission lines.

Keywords: Optimal power flow modeling, power constraints, transmission systems.

Introduction
With electrical power consumption growing annually worldwide, utilities and Transmission System Operators (TSOs) are faced with increasing congestion management, overloading, bottlenecks, and even costly blackouts.

Additional power generations that are adopted as measures to respond to the increasing power demand further strain the available network links (transmission systems). It is therefore becoming essential to upgrade the existing network with optimized solutions and/or expand it with new lines to improve the reliability of the grid while respecting the design criteria and assuring sustainable energy supply far into the future.

The electric power transmission system is a robust network whose optimization requires lots of problem formulation. This is a very huge task for the transmission system operators and engineers alike. Operation and planning of electric power systems involve even a long list of challenging activities, many of which are directly or indirectly related with the optimization of certain objective functions.

The goal of optimization of an electric power transmission system is to minimize (or maximize) objective functions such as: investment/running cost, transmission loss, voltage deviation, etc subject to operational constraints of the power system. In analyzing the optimization problem, there are many controllable parameters of interest. There are also many objective functions and constraints that must be satisfied for economic operation. It must be noted here that while the constraints on optimization are widely recognized, the basic problem formulations must be utility specific. This ensures that the solutions to the goals of optimizing the objective functions are also utility specific.

Methods exist for solving the resulting economic dispatch problems as a function of time, when we incorporate the constraints of the system. In all these methods, Power system operators try to reduce power losses, improve system security with a minimum set of control actions (Mehta and Mehta,1982), minimize the load to be shed, etc. All of these are particular cases of the so-called optimal power-flow (OPF) problem (Morrow and Brown, 2007).

Electricity Transmission Optimization involves majorly two areas – Optimal Power Flow (OPF) models and – Transmission Network Expansion Planning (TNEP) models. In this paper though, priority is given to the optimization of power flow models so as to identify the best solution to transmission system constraints. The emphasis made on TNEP is that, the identification and application of optimal TNEP model is in itself, a reduction in the operational constraints of the transmission system.

Among the distinctive features of power system optimization problems, the following are of most importance:

- large number of variables and constraints, particularly in medium-term operational and planning problems;
- non-convexity of the objective function in many practical cases;
- Presence of integer variables to model on/off status of certain devices, existence of a feeder section, etc.

In recent years especially in Nigeria, there has been interest in applying various optimization models for power system problems so as to attain optimality in the system operations. Many of these models focus on the constraints related to the steady state operation of the network. In most cases, security constraints (i.e. operation of the power system under credible contingencies) are not considered in detail.

This paper is prepared to cover the optimization of the electric transmission system with considerations on the system constraints - (security constraints inclusive). Over the years a wide variety of different solution approaches have been proposed.

The selection of the appropriate optimization technique depends on the system as defined by the objective function and constraints. Mathematical techniques such as linear programming, LP, unconstrained optimization techniques (using Lagrange multiplier) and non-linear and mixed non-linear programming to accommodate the constraints exist.

The constraints are divided into two classes, namely technical and non technical constraints. Technical constraints include network, equipment and devices constraints while the non technical constraints include social, environmental and economic limitations.

Methodology and model

The optimization of electric power transmission system follows a stepwise process. First is to have a good knowledge and understanding of the system configuration. In order to obtain the best cost performance result, it is important to consider altogether the relevant options and possibilities in the first stages of study, when the basic system conception is defined. In fact, some interesting solutions imply in joint measures and coordinated choices, and can hardly be detected if different aspects are dealt with separately or sequentially, as it is done in many system studies.

The joint evaluation of different aspects is critical when non-conventional solutions are considered, as it is the case of long distance transmission systems, for which extrapolation of common practice would lead to solutions quite far from optimum.

In order to obtain an optimized solution, considering investment cost, losses, reliability and flexibility to different load increase rates, it is necessary to consider simultaneously all relevant options and parameters, identifying ranges in which basic constraints are met and optimum solution must be searched.

Second is the problem formulation adopting the optimal power flow models (OPF) which may be classified as:

- Basic OPFs.
- SCOPF: additional security constraints.
- SCOPF-VS: SCOPF with voltage stability constraints (Panos, 2010).

Optimal power flow formulation

The standard/general optimal power flow problem can be written as

$$\begin{aligned} &Min\, f(x_c, x_s) \\ &s.t.\ h(x) = 0, \\ &g(x) \leq 0, \\ &x_{min} \leq x \leq x_{max}\,. \end{aligned} \qquad (1)$$

Where

x_c and x_s are the control and state variables respectively, x is the independent variable such as the generated real and reactive powers, generation bus voltage magnitudes, transformers taps etc.

OPF is formulated mathematically as a general constrained optimization problem as

Minimize a function $f(u,x)$

Subject to $h(u,x) = 0$ (2)

And $g(u,x) \leq 0$

Where, u is the set of controllable quantities in the system and x is the set of dependent variables (state variables), $f(u,x)$ is the objective function and is scalar. Equality constraints $(h(u,x))$ are derived from conventional power balance equation while the inequality constraints $(g(u,x))$ are limits on control variables u and the operating limit on the other variables of the system. The equality and inequality constraints include the power flow equations, generation/load balance, generator

Mvar limits, branch flow limits, and transmission interface limits.

The essence of the optimal power flow problem is to reduce the objective function and simultaneously satisfy the equality constraints without violating the inequality constraints.

Objectives of OPF

The objective of OPF could be any of the following, a combination of them, or a multiple objective.

- Minimize the generating cost,
  $C_G = \sum_{i=1}^{ng} a_i + b_i P_{gi} + c_i P_{gi}^2;$ (3)
- Minimize real power loss and Volt-Ampere Reactive (VAR) power cost;
- Minimize the deviation from a specified point of control variables;
- Etc.

The most common objective of the OPF problem is the minimization of the total cost of real power generation. The individual cost of each generating unit is assumed to be a function of real power generation and is represented by quadratic curves of second order. The equation in (3) shows the sum of the quadratic model at each generator, where ng is the number of generation, including the slack bus. P_{gi} is the generated real power at bus- $i, a_i\ \ b_i\ and\ c_i$ are the unit costs curve for i^{th} generator.

Optimal power flow constraints

- Power flow constraints (real and reactive power balance)
- Rotor-angle constraints
- Limits on both control and state variables
  - Real and Reactive power generation limits
  - PV and PQ bus voltage limits
  - Bus transient voltage limits
  - Transmission line flow limits
  - Transmission line power oscillation limits

The constraints are basically classified as – equality and inequality constraints.

Equality constraints

While minimizing the cost function, it is necessary to make sure that the generation still supplies the load demands (P_d) plus losses in the transmission lines. Usually the power flow equations are used as equality constraints:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} P_i(V,\theta) - (P_{gi} - P_{di}) \\ Q_i(V,\theta) - (Q_{gi} - Q_{di}) \end{bmatrix} = 0 \quad (4)$$

Where real and reactive power injection into bus- i are defined in the following equation:

$$P_i(V,\theta) = \sum_{j=i}^{nbus} V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) i \quad (5)$$

$$Q_i(V,\theta) = \sum_{j=i}^{nbus} V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij \cos\theta_{ij}}\right) i \quad (6)$$

Where g_{ij} is the conductance, b_{ij} is the susceptance, V_i is the magnitude at the bus- i and θ_{ij} is the bus voltage phase angle.

Inequality constraints

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security. The most usual types of inequality constraints are upper bus voltage limits at generations and load buses, lower bus voltage limits at load buses, var. limits at generation buses, maximum real power limits corresponding to lower limits at some generators, maximum line loading limits and limits on tap setting of phase shifter. The inequality constraints on the problem variables considered include:

- Upper and lower bounds on the real generations at generator buses:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}, i = 1, ng \qquad (7)$$

- Upper and lower bounds on the reactive power generations at generator buses and reactive power injection at buses with VAR compensation:

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}, i = 1, npv \quad (8)$$

- Upper and lower bounds on the voltage magnitude at all buses:

$$V_i^{min} \leq V_i \leq V_i^{max}, i = 1, nbus \quad (9)$$

- Upper and lower bounds the bus voltage phase angles:

$$\theta_i^{min} \leq \theta_i \leq \theta_i^{max}, i = 1, nbus \quad (10)$$

- Upper and lower bounds on branch MW/MVar/MVA flows may come from thermal ratings of conductors, or they may be set to a level due to system stability concerns:

$$\left|S_{ij}\right|^2 = S_{maxij}^2 \quad (11)$$

It can be seen that the generalized objective function f is non-linear, the number of the equality and inequality constraints increase with the size of the power distribution systems.

Transmission system constraints

The amount of power on a transmission line is the product of the voltage and the current and a hard-to-control factor called the “power factor”. Additional power can be transmitted reliably if the there is sufficient transmission capacity on all lines in the system over which the power would flow to accommodate the increase and certain contingencies of failures that could occur on the system. There are three types of constraints that limit the power transfer capability of the transmission system and they are:- thermal/current constraints, voltage constraints, and system operating constraints.

Thermal/current constraints

Thermal limitations are the most common constraints that limit the capability of a transmission line, cable, or transformer to carry power. The power handling ability of a line is limited by the thermal loading limit and stability limit. The increase in the conductor temperature, due to the real power loss, stretches the conductors. This results in increased sag between transmission towers.

Transmission lines resist the flow of electrons through it, causing heat to be produced. The actual temperatures occurring in the transmission line equipment depend on the current, which is the rate of flow of the electrons, and also on ambient weather conditions.

The thermal ratings for transmission lines, however, are usually expressed in terms of current flows, rather than actual temperatures for ease of measurement. The thermal limit of line conductors is specified by the current carrying capacity of the conductors and is usually denoted by $I_{thermal}$, the thermal loading limit of a line is

$$S_{thermal} = 3V_{\emptyset rated}\, I_{thermal} \quad (12)$$

The expression for real power transfer over the line for a lossless line is given by

$$P_{3\emptyset} = \frac{|V_{S(L-L)}||V_{R(L-L)}}{X'} \sin\delta \qquad (13)$$

The theoretical maximum power transfer that can be transmitted under stable steady state condition occurs at an angle (δ) of 90°. The practical operating load angle for the line alone is limited to no more than 30 to 40°. This is because of the generator and transformer reactances which, when added to the line, will result in a large δ for a given load (Hadi,1999).

Thermal limits are imposed on transmission links because over heating leads to two possible problems:

(1) The transmission line loses strength which can reduce the expected life of the line, and
(2) The transmission line expands and sags in the centre of each span between the supporting towers leading to irreversible stretching.

Voltage constraints

Voltage is a measure of the electromotive force necessary to maintain the flow of electricity on a transmission line. Voltage fluctuations can occur due to variations in electricity demand and failures on transmission or distribution lines.

Constraints on the maximum voltage levels are set by the design of the transmission line. If the maximum voltage level is exceeded, short circuits may occur, leading to abnormal power flows in the network. Also, transformers and other equipment at the substations and/or customer facilities may be damaged or destroyed. Minimum voltage constraints also exist based on the power requirements of the customers. Low voltages cause abnormal operation of customer´s equipment and may damages motors and compressors.

Voltages on transmission lines tend to "drop" from the sending end to the receiving end. The voltage drops is almost directly proportional to reactive power flows and line reactance. The line reactance increases with the length of the line. Capacitors and inductive reactors are installed, as needed, on lines to control the amount of voltage drop. This is important because voltage levels and current levels determine the power that can be delivered to the customer.

System operating constraints

The operating constraints of bulk power systems stem primarily concerns with security and reliability [6]. These concerns are related to maintaining the power flows in the transmission and distribution lines of a network.

Preventive operation for system security

Constraints on the transmission capabilities also occur due to preventive operating procedure for security. The bulk power system is designed and operated to provide continuity of service in the case of possible contingencies such as: loss of a generating unit, loss of a transmission line, or a failure of any other single component of the system. "Preventive" operating procedures mean operating the system in such a way as to avoid service interruptions as a result of certain component outages.

System stability

Voltage instability occurs when the transmission system is not adequately designed to handle reactive power flows. Large amounts of reactive power flows on long transmission lines result in severe drops in voltage at the consumption end, causing the consuming entities to draw increasing currents. The increased currents cause additional reactive power flows and voltage losses in the system, leading to still lower voltages at the consumption end. As the process continues, the voltages collapse further, requiring users to be disconnected to prevent serious damage. Finally, the system partially or fully collapses .

Conclusion and recommendations

In this study report, it has been made clear that the optimization of an electric power transmission system follows a stepwise but rigorous process which is seen as a difficult task to transmission system operators and optimization experts alike. The choice of optimization technique or approach for any case study depends on the configuration of the system and the specific objectives of the optimization. This is so because, it is not in all cases that minimization of transmission cost is given utmost attention. Some investors may want a very robust, flexible and at the same time, rugged system. In such a situation, a compromise will be made on cost and the optimization approach or the algorithm to arrive at such an objective will definitely differ from the usual approaches. So many optimization algorithms or methods have been proposed but the uniqueness of networks makes it challenging to pick the best of the algorithms.

The various identifiable constraints that have been described in this paper, limit transmission system′s capacity to transfer power and therefore, lower the utilization rates of the existing transmission network. Thus, there is the need for system upgrade and expansion/reinforcement to ensure that more power is transmitted reliably and close to line limits without threats to system security. It remains the exclusive reserve of system planners to choose which constraints that should be remedied. Some remedies for the constraints described above are outlined here.

Remedies for thermal constraints on components: - Many options are available for reducing the limitations on power transfer due to the thermal rating of overhead transmission lines. The thermal limit of transmission lines is based on the component that would be the first to overheat. Thus a substantial increase in the overall thermal rating of the line can sometimes result from replacing an inexpensive element. The replacement of a disconnect switch or circuit breaker is much less expensive than the task of replacing a line or to build a new line.

It may also be possible to increase the transfer capability of the line by monitoring the line sag to allow higher temperatures/current. There two possible approaches, one direct and the other indirect. The direct approach involves calculating the actual sag of the line at its mid-span using actual information provided by special sensors on the towers about the horizontal tension and ambient temperature. Using this method, the control center calculates the actual limit on the current that the line can handle under actual conditions. The indirect method entails transmitting temperatures and wind velocity and locations of the critical sag sites to the control center by radio or telephony. With this information, the control center calculates what the sag is and determines any dangerous trend.

The most obvious, but also most expensive method for alleviating the thermal constraints on the line is to replace the lines with larger conductors through “restringing” or add one or more lines, forming “bundled” lines. This approach requires consideration of the tower structures that support power lines. The towers are designed to carry the weight of the existing lines and the weight of any possible ice formations. They require lateral strength to withstand the sometimes very substantial forces of winds blowing perpendicular to the direction of the line.

Replacing lines with large ones, or bundling them, usually requires substantial reinforcement of the tower structures and, possibly, the concrete footings of the towers. Restringing or bundling lines to increase the transfer capability also requires enhancing substantial equipment so that it does not become a limiting factor.

Since the objective is to increase capacity and transmission network reliability at reasonable cost, transmission planners also want to re-use existing towers and installations to save time, and avoid very long right-of-way authorizations. Therefore, to do more with the same structures mean that you have to replace lines with new conductors that can deliver higher ampacity, operate safely at higher temperatures, without straining towers and pylons, or generating dangerous sag. Moreover, real-time monitoring systems, installed directly on the lines are a good solution to further improve the operating capacity and reliability of the network.

To achieve higher capacity with reduced capital investment, it is now feasible to use fewer towers and longer conductor spans. This means incorporating the latest generation of carbon core conductors which are lighter and offer higher mechanical strength.

These new conductors can also be designed to operate at higher temperatures, thus allowing temporary or permanent increases in capacity, and strengthening the reliability of the network.

Remedies for voltage constraints: - All transmission line types can carry 5 percent more or less voltage for normal operation. Upgrades to change line voltages can be divided into two categories: increase within a voltage class and changes to a different voltage class.

Increasing the operating voltage within a voltage class is a technique that has been used for decades. If the system does not reach the upper limit during light loads under normal operation, normal operating voltage can be increased without major configuration changes to the lines. It is necessary, however, to increase the voltages of the generators, and to make some adjustments to the settings of the transformer. Coordination with neighboring systems is required to prevent additional reactive power flows because of the increased voltage into the neighboring system.

Other remedies for voltage problems that limit transfer capabilities involve controlling reactive power flows. There are two types of reactive power sources, capacitors, and reactors, which generate and absorb reactive power flows respectively. The installation of capacitors or reactors at strategic locations of the transmission or distribution system is a remedy often used to control reactive power flows and therefore increase power transfer.

Remedies for system operating constraints: - The power flow can be altered by reducing the impedance of the line through the insertion of series capacitors or by increasing the impedance through the insertion of series reactors. As impedance is reduced, voltage drops along the lines are also reduced. This process helps to reduce the amount of reactive power losses on the lines.

Capacitors increase the flow on the line on which they are inserted and reduce the power flow on other parallel lines. Series reactors reduce the power flowing through a line which otherwise would be overloaded, but are used less often than capacitors.

References

CSA Energy Consultants, *"Existing Electric Transmission and Distribution Upgrade Possibilities"* Arlington V. A, pp. 9, 1995.

Hadi, S. (1999), *Power System Analysis*, Milwaukee School of Engineering, New Delhi. McGraw-Hill Publishing Company Limited.

Mehta V. K and Mehta, R. (1982) *Principles of power system,* New Delhi, S. Chand & Company Press.

Morrow, D. J. and Brown, R. E.(2007) "Future Vision – The Challenge of Effective Transmission Planning"

IEE Power and Energy Magazine, Pp. 36 – 45 Sept/Oct .

Panos, M. P.(2010) *Computational Algorithms for Power Systems Optimization*, Conference on "Energy, Sustainability and Climate Change" February 26 - 28, University of Florida Gainesvill.

Rafik, L., Slimani, L. and Bouktir, T. *Particle Swarm Optimization Applied to the Economic Dispatch Problem,* Electrical Engineering Department, Oum El Bouaghi University, 04000 Algeria. rlabdani@yahoo.fr

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