SOLVING OPEN ACCESS TRANSMISSION AND SECURITY ANALYSIS PROBLEMS WITH THE SHORT-CIRCUIT CURRENTS METHOD✦

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Abstract This paper describes two applications of Paul Dimo's short-circuit currents method based Nodal Analysis -- *real-time external network modeling* in an energy management system by using the REI-Dimo equivalent for security analysis, and *fast maximum transfer capability prediction* based on Paul Dimo's short-circuit currents technique for steady-state stability analysis. These solutions are fine examples of how utilities can benefit from the simple, yet powerful and field-proven Nodal Analysis to solve some of the problems arising from the open-access transmission paradigm.

INTRODUCTION

Power system equivalents were used originally to represent networks that were too large for the limited capabilities of network analyzers and early digital computers. Subsequently they became useful in loosely defined planning scenarios and energy management systems (EMS) network analysis, i.e., in applications where accurate network models of systems external to the study-area are not available.

Equivalents have also been used to speed up and simplify the complex computational algorithms. For example, the rigorous solution of the steady-state stability problem is predicated on detailed machine models and entails an alternate sequence of load-flows and eigenvalue calculations until the point of instability is found. But determining eigenvalues for successively deteriorated load-flow cases is computationally intensive and has the inconvenience that load-flows may not converge near instability. The use of equivalents in conjunction with appropriate simplifying assumptions is the only way to overcome such difficulties.

The Nodal Analysis, [6], [7], [8] developed by Paul Dimo in Europe in the 1960s provides fast and reasonably accurate solutions to otherwise difficult problems. It uses a bus-reduction technique known in the United States as REI-Dimo Equivalencing [10], [11], [18], [21], [25] and represents the effect of generators and tie-line imports upon the system load and tie-line exports by means of *short-circuit currents*.

The short-circuit currents flow *radially* from generators and tie-buses to loads, actual or equivalized, through short-circuit reactances [2], [6], which explains the acronym *REI* (*R*adial-*E*quivalent-*I*ndependent). They form the basis for the voltage stability solution technique developed by Barbier and Barret [2], and are used in Paul Dimo's *case worsening procedure* for determining the steady-state stability limit [5].

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Advanced security analysis equivalents seemed to fall in oblivion when state estimation techniques were developed to extend the network observability with external areas by using pseudomeasurements and telemetry data, if available. So, the general feeling was that accurate equivalents may not be needed any longer, although off-line load-flow programs still use the old Ward model, or its enhanced version known as "extended Ward", as a simple, even if not accurate, way to represent areas where data are not available.

The advent of the open access transmission paradigm in recent years, however, posed new challenges to the research community: the accurate calculation of *parallel flows;* and the computation of *maximum transfer capability* limits that preserve the system's stability.

The computation of parallel flows was approached via distribution factors determined off line via DC load-flows, [24], [36], and no other solution appears to be in sight. It is believed that this difficult problem can be effectively solved by using multi-area REI-Dimo equivalents in the same way they were successfully implemented and used in production-grade operations throughout the 1990s at Empresas Públicas de Medellín (EPM) to represent the multi-utility system of Colombia[17], [22]. The method to build and update such network equivalents is described in the first part of this paper.

The determination of maximum transfer capability limits that take into account stability has been neglected by most EMS vendors and researchers – current ATC calculators do not go beyond using DC or AC load-flows to check thermal violations. But a fast and field-proven steady-state stability analysis method has been available for a number of years. Its core algorithm was developed in Europe [5], [8], [34], and validated in two EPRI research projects [1], [23], [31]. An application using this approach was first installed experimentally in US and Canada [12], then upgraded for production-grade use in daily operations. It finds the steady-state stability margin of a 1300 bus system in 1 second on a laptop and is currently implemented in several SCADA/EMS installations. The underlying solution technique is Paul-Dimo's short-circuit currents approach to steady-state stability assessment and is addressed in the second part our paper.

PART I: REI-DIMO EQUIVALENTS
The Equivalencing Problem

Power systems consist of a: *linear sub-system*, i.e., transmission lines, transformers, reactors, capacitors and the bus-to-ground admittances used to represent line charging and transformer taps; and a *non-linear subsystem*, i.e., generators, loads and synchronous condensers. Buses can be divided into non-*essential buses*, which are to be eliminated, and *essential buses*, which are to be retained unchanged.

Power system networks can't be reduced by applying the star-delta transformation because of the non-linear nature of the bus injected MW and MVAr powers and, therefore, approximate methods have to be devised. There are many variations on how to deal with equivalencing, but it is generally recognized that a suitable equivalent model should meet a number of accuracy, computational and topological requirements including:

- seen from its boundaries, the equivalent should represent *accurately* and *reliably* the behavior of the power system
- the reduced model should reproduce as close as possible the *physical nature* of the power system to be replaced
- the equivalent should be flexible enough to handle power system status changes and to be used in a wide range of applications
- the equivalent should be compatible with the computational procedures used to solve subsequent problems
- the equivalent should insure that feasible mathematical solutions are obtained
- the reduced network should contain as small a number of nodes as possible.

Among the various solution techniques proposed in the literature, the REI-Dimo methodology stands out because of its very unique concept of *linearizing the injections of the same type by replacing them with constant admittances, then grouping them back into a single non-linear injection applied to a fictitious bus called REI bus*. This process is made possible by introducing a fictitious network, between the buses to be eliminated and the fictitious REI buses, which is linear, has no losses and can be eliminated by simple Gaussian reduction. This network is referred to as *Zero Power Balance Network* and represents the central concept in the REI-Dimo methodology.

The Zero Power Balance Network

The linearization-delinearization process uses a temporary network between non-essential buses and the REI buses. This network, which is referred to as *Zero Power Balance Network*, is linear, has no losses and may be eliminated by Gaussian reduction. The Zero Power Balance Network is built as follows:

- for each non-essential node, separate the injected complex power into parts to be aggregated into fictitious generators and fictitious loads, respectively, then replace, i.e., *linearize* them with constant admittances
- extend the original network by adding the fictitious REI buses <u>and</u> one fictitious ground for each fictitious REI bus (the new admittances, voltages, powers and currents are calculated with the formulae (5)-(9) in [21])
- calculate the equivalent injections at the fictitious REI buses by adding the complex powers which were aggregated into those buses. For example, on the single-load REI bus, the injected load is going to be the sum of all the bus loads that were aggregated, i.e., the total system MW and MVAr load.

Before applying the Zero Power Balance Network algorithm one must specify:

- how many REI generator buses are needed and which machines are to be aggregated into each REI generator bus
- how many REI load buses are to be introduced, which is the pattern of aggregating loads into the REI load bus(es) and whether to *include in the REI load bus(es) some or all the loads from the essential buses*.

The reliability and accuracy of the equivalent depend upon the number and specification of REI buses. The rules for aggregating injections into REI buses, extensively discussed in [7], [21], [22] [28] and [34], are briefly summarized in the following.

REI-Dimo Equivalents for Security Analysis

The simplest method to build an REI-Dimo equivalent for security analysis is to specify <u>*one*</u> REI generator bus for the total system generation and <u>*one*</u> REI load bus for the total system MW and MVAr load <u>*for each one*</u> of the external sub-systems. In other words, if the external area encompasses several utilities, there will be one REI generator and one REI load for each utility. This approach has been successfully used by various power utilities such as Southern Company Services [18], Centerior Energy Corporation [11], American Electric Power [10], Bonneville Power Administration [25], Empresas Públicas de Medellín [15], [19].

More elaborate procedures have also been proposed, e.g. the method described in [21] which consists of grouping the generators and synchronous condensers in accordance with *classes of REI equivalence*, then associating each class with an REI generator bus.

After the REI buses and related aggregation pattern were specified, the MW and MVAr generations, bus voltage magnitudes and angles, MW and MVAr loads and network topology data are taken from the base-case, the Zero Power Balance Network is built and the Gaussian reduction is applied. The final result is an REI-Dimo equivalent that is to be connected both to the internal system, at the boundary buses, and or to other REI-Dimo equivalents built to represent the remaining external areas.

Updating REI-Dimo Equivalents for Security Analysis

In order to illustrate the data methods available for updating REI-Dimo equivalents in security assessment systems we assume that each external utility network is represented by an REI-Dimo equivalent with *one REI-Dimo single-load bus* that aggregates the entire company's MW and MVAr load, and *one REI-Dimo equivalent generator bus* that aggregates all the external company's generators and synchronous condensers. Should the external interconnection encompass more than one utility, *an REI-Dimo equivalent shall be formed for each utility and subsequently interconnected through actual tie-lines and/or essential lines and buses from the external system*.

REI-Dimo equivalents for security analysis can be updated:

- *in real-time* with the total company's load and generation data that are readily available in modern energy management systems
- *off-line* with pseudo-measurements such as external company's load and generation data available either by phone or from the operations planning data base.

Generator outages, system or bus load changes and shifts in the external generation and system interchange can be appropriately reflected by simply adjusting the injection(s) on the REI-Dimo equivalent generator bus(es) and REI-Dimo single-load bus(es) used to represent the external system(s).

To the extent the network of REI-Dimo equivalents also contains essential lines and buses, the capability exists to instantly represent line and/or transformer outages, transformer tap changes and shunt capacitor and shunt reactor outages.

Testing and Validating REI-Dimo Equivalents for Security Analysis

A critical issue when dealing with external equivalents is how to test and validate them.

As a rule of thumb, after the external area was replaced with an equivalent, e.g., an interconnection of REI-Dimo equivalents, a testing scenario must be defined which covers 100%, 75% and 50% of the system load and combines it with a significant variety of generation outages and single and double line contingencies in the internal system.

For all the study cases included in the above scenario, the tie-line MW and MVAr flows must be monitored and compared against values obtained from full power-flow calculations conducted on the complete (unreduced) model. Monitoring the bus voltage magnitudes on the boundary buses is irrelevant since small errors on these voltages might translate in relatively large errors on the line flows. The methodology for testing and validating of REI-Dimo equivalents has been described in [22] and further illustrated with results from the EPM EMS implementation in [15], [19].

REI-Dimo Equivalents for Steady-State Stability Assessment

A variation of the previously described algorithm allows building single-load equivalents with all the machines represented, which are suitable for steady-state stability assessment. First, the MW and MVAr generations, bus voltage magnitudes and angles, MW and MVAr loads and network topology are retrieved from a solved power flow case (base case). In addition, the transient and synchronous reactances of all the machines (generators and synchronous condensers) must be provided, along with the reactances of the transformers between machines and the high voltage buses. If the network encompasses several sub-areas, the short-circuit reactances of each external sub-area as seen from the points of interconnection (tie-line buses) must be calculated and the active injection represented as a generator. Tie-line exports are represented as loads

The equivalencing procedure is applied as follows:

- remove all the active elements with the exception of generators, synchronous condensers and tie-line buses (imports)
- define a fictitious single-load REI bus that aggregates the system MW and MVAr load, including tie-line exports
- define a fictitious load-neutral bus
- connect the fictitious load-neutral bus with all the active buses that are to be eliminated with admittances that linearize and replace the removed MW and MVAr loads
- connect the fictitious load-neutral bus with the single-load REI bus through an admittance calculated in accordance with the Zero Power Balance Network procedure
- define an internal bus for each generator and synchronous condenser and include it in the set of active buses
- connect the generator (synchronous condenser) buses with the internal buses through admittances derived from the transient or synchronous reactances of the machines, depending upon the MVAr loading of the unit (also include the transformer's reactance where applicable)
- calculate the new complex generated powers (same MW but new MVArs) and bus voltages on the internal buses
- eliminate all the passive buses in the extended network including linearized buses, the fictitious load-neutral bus and all the buses that were passive prior to extending the system with the Zero Power Balance Network and the transient or synchronous reactances of the machines.

The result is an REI-Dimo equivalent that contains:

- all the generators, synchronous condensers and tie-line imports represented explicitly as active buses with MW and MVAr values taken directly from the base case and bus voltages computed behind the transient or synchronous reactance of the machine
- one single-load REI bus where the entire system MW and MVAr load is concentrated; and the complete set of links between the equivalent's nodes.

What is remarkable about this REI-Dimo equivalent is that *it meets the theoretical conditions to be virtually exact* [21], [29].

PART II: REI-DIMO METHOD FOR STEADY-STATE STABILITY ASSESSMENT

The Steady-State Stability Problem

Steady-state stability is the stability of the electric power system under gradual or relatively slow changes in load. This concept refers to power system states permanently subjected to *infinitely* small changes. Such states are said to be unstable, from a "static" point of view, if they're unable to provide for uninterrupted service. Instability can be identified either by exact calculations or via practical criteria. The phenomenon of steady-state instability doesn't happen at once. The states are said to be *far* from, or *close* to a ***critical point*** depending upon how close is the "dynamic-state" Jacobian matrix from the point of singularity. Some authors say *steady-state stability reserve* for a given power flow case, to refer to the distance from the critical state.

The conventional method of the small oscillations for estimating the steady-state stability, [4], [8], [20], [27], [33] consists of examining the eigenvalues of the characteristic equation associated with the system of differential equations that describe the free transient processes after a small disturbance takes place in an automatically controlled power system. The *necessary and sufficient condition for steady-state stability* is that all the real parts of the eigenvalues of the characteristics equation be negative [26, pp. 215]. The approach is laborious, computationally intensive and requires data that may not be readily available. For practical purposes, it entails simplifications (such as neglecting the inertia constants of the machines and representing the loads as constant impedances) that may offset the benefits of an otherwise exact methodology.

In practice, the solution of a high-order characteristic equation is replaced by *algebraic* (Routh-Hurwitz) criteria. A *necessary* condition for steady-state stability is derived from the Routh-Hurwitz criterion by evaluating the sign of the last term of the characteristic equation, i.e., the dynamic-state Jacobian matrix determinant [20]. A change of sign with further loading of the system corresponds to aperiodic instability. The instability in the form of self-oscillations, however, remains unrevealed by this method [28]. A further simplification is to use the "load-flow" Jacobian [2] instead. Sauer and Pai [20] have shown that the "load-flow" Jacobian provides an *upper-bound* of the steady-state stability limit.

Based on practical considerations, further simplifications can be made. Fore example, we may assume that some operating variables are constant. Then the condition that the dynamic-state Jacobian be singular lead to *practical* criteria that are valid within certain limits. For a network of active buses connected radially to a nodal (load) point, the practical criteria are stated as follows:

- $dP/d\delta > 0$, also known as the *synchronizing power criterion* [4], [8], [28] -- it assumes constant frequency, constant voltages at the nodal point and constant turbine power
- $dQ/dV < 0$, also known as the *reactive power criterion* [5], [8], [28] -- it assumes that the frequency is constant, the network consists of a multimachine system having a nodal point and the real power balance is maintained at the load node
- $dP/dV < 0$, or the *voltage stability criterion* which is typically used in voltage stability assessment [2], [9], [17], [26] and identifies the point of voltage collapse at the nodal point.

Paul Dimo has shown that, for a system of 1, ..., m generators and synchronous condensers connected radially to a single-load bus (either actual or equivalized) through the admittances Y_1, ... Y_m, the dQ/dV derivative can be computed with formula (1)

$$\frac{dQ}{dV} = \sum_m \frac{Y_m E_m}{\cos\delta m} - 2\left(\sum_m Y_m + Y_L\right)\cdot V \qquad (1)$$

where: E_m = internal voltages of the machines (assumed to remain constant, unaffected by small adjustments made under steady-state stability conditions); δ_m = internal angles of the machines with reference to the voltage e on the single-load bus; and the reactive load varies with the square of the voltage in accordance with formula (2):

$$Y_L = \frac{Q_{Load}}{V^2} \qquad (2)$$

He also demonstrated that, for radial networks, $dQ/dV = 0$ when the dynamic-state Jacobian be singular. The mathematical proof can be found in reference [8, pp. 73-74] and has been illustrated by an example in [22].

From this analysis it can be inferred that:

- the point of steady-state instability is also the point of maximum power transfer, as well as the limit of voltage stability
- voltage stability cannot be separated from the system-wide steady-state stability conditions. More exactly, the phenomenon of voltage collapse, which is typically perceived within localized areas, occurs simultaneously with the steady-state instability of the entire system, i.e., at the point of singularity of the dynamic-state Jacobian when its determinant becomes equal to zero.

REI Nets. Short-Circuit Currents. Nodal Images

The REI-Dimo equivalent built specifically for steady-state stability analysis contains all the active buses, i.e., generators and tie-line injections, and one load bus, which is the single-load REI bus. The *graph* associated to this equivalent will contain G + 1 buses, where G is the number of generators, and (G + 1) * (G + 2) / 2 edges. If we now extract the *sub-graph* containing just the single-load REI bus (designated as bus i) and its links (edges) with the generator buses (designated as m), we obtain the ***R****adial-****E****quivalent-****I****ndependent (REI) Net* of that bus [7], [9].

On the other hand, the currents flowing from generators to the load bus are the short-circuit currents. Therefore, the admittances (impedances) of the so-called REI Net are, in fact, nothing else but the short-circuit admittances (impedances) identified with this name in [2].

Using the conventional matrix form of the node transformation, the equation $I_m = \Sigma Y_{im} V_m$ written for the nodal point, i.e., the load bus in [2] or the single load REI bus, in Paul Dimo's Nodal Analysis, simply says that the load current at bus m is the sum of currents flowing from the other (active) buses towards m across admittances Y_{im}, which clearly corresponds to a radial network paradigm.

Paul Dimo introduced another innovation: the *Nodal Image*, which is a vectorial representation of the short-circuit currents in a Cartesian space where *Ox* corresponds to the reactive component, and *Oy* corresponds to the active (real) component of the short-circuit currents [6], [8]. The actual graphical representation is irrelevant for this paper, but the associated equations are used to formulate the *case worsening procedure*'s algorithm (see below).

Modeling Assumptions

REI Net of Reactances Since the practical steady-state stability criteria apply to radial networks, and since the network of short-circuit reactances, or the REI Net, is radial, the first step is to replace the equivalent with an REI Net. For the base case, this substitution is exact and is supported by Fallou's theorem [5], [6], [7], [8].

For other states, i.e., when the base conditions are degraded to approach instability, the approximation implied in neglecting the equivalent's lateral links is necessarily small. The generated power must cover both the load and the losses, and since the equivalent network has only one load bus, most of the system power flows from generators towards the single-load REI bus and only a small fraction of it circulates on lateral links.

The next simplification consists of replacing the complex impedances of the REI Net with reactances. Voltages could be recomputed to compensate for this approximation but in high voltage transmission and sub-transmission networks the values will be practically the same. In all the test cases studied in conjunction with [31] and [32], the R/X ratios for the equivalent's radial branches had values between 0.05 and 0.01, i.e., R was found to be from twenty to one hundred times smaller than X. Incidentally, two decades of practical experience with the Paul Dimo's Nodal Analysis, amply documented in [8] and related references, clearly indicated that using an REI Net of reactances is a safe approximation.

Use of dQ/dV in Conjunction with the REI Net A key simplifying assumption consists of evaluating the steady-state stability via dQ/dV for the REI Net rather than computing the load-flow Jacobian determinant for the entire network. As stated earlier, this is possible because the REI Net is extracted from a special form of REI-Dimo equivalent that meets the theoretical conditions for exactness since:

- the dQ/dV criterion applies to a network of machines connected radially to a single node [27], condition that is clearly met by the topology of the REI Net
- generators, synchronous condensers and tie-line injections are represented in detail
- MW and MVAr loads are aggregated in an equivalent load center, which is a good approximation for conforming loads [29].

Load and Synchronous Machine Models The following load and synchronous machine models are used:

- generators and synchronous condensers that didn't reach the Q_{max} limit in the power-flow case are represented through their transient reactance x'_d and the voltage E' behind x'_d
- generators and synchronous condensers that have already hit the Q_{max} limit are represented through their synchronous reactance x_d and the e.m.f. E behind x_d
- the machine models are adjusted during the case worsening calculations to reflect the discontinuity that occurs when a synchronous machine reaches its maximum MVAr capability
- the load on the single-load bus is modeled as $P = const$ and $Q = YV^2$

The Case Worsening Procedure

After the use of practical criteria applied to a radial network of short-circuit reactances instead of computing eigenvalues on a full scale network model, the replacement of successive load-flow calculations with the *case worsening procedure* is the next, and very decisive, factor that explains the extremely high speed of the methodology. The case worsening procedure can be used if the following conditions are met:

- the network is radial, which is precisely the case of an REI Net
- the MW power generated by the machines is delivered without losses at the single-load REI bus, which is true because the REI Net branches have no resistance
- the equivalent system load is varying at constant power factor, which is implied in the load model
- the internal voltages E' (or E, depending upon whether the MVAr limits were hit) of the machines are constant.

The case worsening procedure consists of rotating the Nodal Image in small increments and computing, at each step, the system MW generation, the MW and MVAr output for each unit, the voltage on the single-load REI bus and the value of dQ/dV. If a machine hits its MVAr limit, a *model correction step* is performed. The process stops when the *steady-state stability index* $dQ/dV => 0$. The last step where $dQ/dV < 0$ is considered to be the *critical state*.

Various rules for loading the generators can be adopted. The easiest method is to *rotate the generators coherently*, i.e., to use the same angle change both for the system vector and for each individual generator. Alternatively, the system MW increase can be absorbed by the participating units by using AGC or economic dispatch participation factors.

The Distance to Steady-State Instability

The steady-state stability index provides the invaluable ability to answer the stability question with just one single number. But "how stable" is the system? This indicator becomes truly meaningful only after relating it with the *distance* between the current state and the point of instability.

The distance between the current state (base case) and the point of instability is computed as the difference between the total MW generated in the critical state (area generation plus tie-line imports) and the MW system generation (including tie-line injections) in the base case.

Additional Information Obtained from the Nodal image

The nodal image helps conduct an intuitive reasoning and deduct a number of qualitative aspects of the power system state by noticing that the:

- magnitudes of the phasors $Y_m E_m$ depend upon the field currents of the synchronous machines
- *projections* $Y_m E_m / \cos\delta_m$ indicate the impact of generators and synchronous condensers on the steady-state stability of the system being analyzed -- this property is used by the steady-state stability assessment software described in [12], [29] and the newsletters available on http://www.scscc-us.com
- angles δ_m of these phasors depend upon the MW loading of the generators -- this property is used by the steady-state stability assessment software described in [13], [31] and [32] as an alternate ranking criterion
- bus voltage magnitude V represents the weighted average of the load bus voltages in the actual system and gives an indication about the system's voltage profile.

After the case worsening algorithm has converged and the *critical* power has been computed, a power system state is identified where the total generated system MW power is x% below the critical power. This state is called *marginal state* and corresponds to the hypothetical situation where the total generated power would be x% less than the MW power supplied in the critical state, i.e., right before becoming unstable. The x% parameter is called *security margin*.

An *optimal* state in regard to steady-state stability is also defined which corresponds to the co-linear position of the full-load short-circuit current phasors of the participating units and, as shown in [8], corresponds to the maximum value of the dQ/dV index.

Practical Implementation

This methodology provides the unique ability to *predict* steady-state instability quickly enough to support on-line decision-making. Knowing the actual loadability of the power system can help *improve security*, by denying transactions that may bring the network close to instability, and *increase revenues*, by authorizing MW transfers that otherwise might have been curtailed. Improved security means fewer or no blackouts. And the increase in revenues from safely wheeling more energy across the system can be substantial. At $1.977/MWh [37], raising the wheeled power by just an average of 10

The attractiveness of meeting these goals in real-time and operations scheduling for same-time use motivated the development of a production-grade quality application. After its experimental introduction under the name QuickStab at Southern Company Services, Birmingham, AL and IREQ d'HydroQuebec, Montreal, Canada [12], the software was continuously enhanced. Now it is known as MultiArea QuickStab, supports multi-area networks, needs just one second to run a 1300 bus steady-state stability case on a 1 GHz PC, and can handle systems encompassing up to 35,000 buses. Due to the physical phenomena involved, however, the size of the steady-state stability study-area, which is automatically retrieved from the base case, is restricted to 2,500 buses.

How MultiArea QuickStab Works The program extracts a single or multiple area from a load-flow or state estimation case; computes the maximum area generation and tie-line imports such that voltage collapse or steady-state instability would not occur within the specified area; calculates the maximum loadability corresponding to a user-defined security index; ranks generators and tie-lines in the order of their impact on stability; and provides information that can help develop remedial actions

Utility Implementations The computational speed, reliability, ease-of-use, and unique user-interface of this application caught the attention of SCADA/EMS implementors. The program was ported in real-time on Compaq Unix and is currently being used on-line in the control centers of CTEEP, Sao Paulo, Brazil, O{PSIS, Caracas, Venezuela, and ETESA, Panama.

CONCLUSIONS

Paul Dimo's enhancement of the short-circuit currents method of analysis, known as the REI-Dimo Nodal Analysis, provides fast and reasonably accurate solutions to security analysis, steady-state stability assessment and other difficult problems. This paper describes two major applications of this technique -- the REI-Dimo equivalents for security analysis, and the short-circuit currents method for fast voltage and steady-state stability assessment.

Both the theoretical background and the testing and operational results obtained to date with practical implementations of these techniques recommend them for further use in both conventional security analysis and open access transmission applications.

REFERENCES

[1] Adapa, Rambabu, "Research Update: Steady-State Stability Monitor", EPRI Journal, October/November 1991, pp. 36-39

[2] Barbier, C., Barret, J.P., "An Analysis of Phenomena of Voltage Collapse on a Transmission System", RGE, volume 89, October 1980, pp. 672-690

[3] Barret, J.P., "L'incident vu par la simulation", Revue Generale de l'Electricite, tome 4, avril 1980 (special issue dedicated to the analysis of the December 19, 1978 blackout in the French interconnected power system)

[4] Crary, S., "Power System Stability", General Electric Series, 3rd edition, October, 1955

[5] Dimo, Paul, "Etude de la Stabilité Statique et du Reglage de Tension", R.G.E., Paris, 1961, Vol. 70, 11, 552-556

[6] Dimo, Paul, "L'Analyse des Reseaux d'Energie par la Methode Nodale des Courants de Court-Circuit. L'Image des Noeuds", R.G.E., Paris, 1962, Vol. 71, 3, 151-175

[7] Dimo, Paul, "Les Models REI: Solution Generale pour l'Informatique des Reseaux d'Eergie", Prix Montefiore 1980, Institut d'Electricite Montefiore, Univ. of Liege, Belgium

[8] Dimo, Paul, "Nodal Analysis of Power Systems", Abacus Press, Kent, England, 1975

[9] Dobson, I., L. Liu, "Immediate Change in Stability and Voltage Collapse when Generator Reactive Power Limits are Encountered", in Proc. International Seminar on Bulk Power System Voltage Phenomena II (pp. 65 - 74)

[10] Dopazo, J.F., Irisarri, G., Sasson, A.M. "Real-Time External Equivalent for On-Line Contingency Analysis", IEEE PES Summer Meeting 1978, paper F 78 674-4

[11] DyLiacco, T.E., Savulescu, S.C., Ramarao, K.V., "An On-Line Topological Equivalent for a Power System", IEEE Trans. on PAS., Vol. PAS-97, Sept-Oct., 1978, pp. 1550-1563

[12] Erwin, R. S, Oatts, M. L., Savulescu, S. C., "Predicting Steady-State Instability" -- IEEE Computer Applications in Power, Volume 7, Number 3, July 1994, pp. 10-15

[13] Hao, S., Papalexopulos, A., "External Network Modeling for Optimal Power Flow Applications", Paper 94 SM 598-3-PWRS, presented at IEEE PES Summer Meeting, July 24-28, 1994, San Francisco, California

[14] Ionescu, S., Ungureanu, B., "The Dual Power States and Voltage Collapse Phenomena", Revue Roumaine des Sciences Techniques, Serie Elect. et Energ., Tome 26, No. 4, pp. 545-562

[15] Jaramillo, J. G., Paternina, E. M., Hoyos, L. A., "External Equivalent for Empresas Publicas de Medellin", IV Simposio Latino Americano sobre Centros de Control, Rio de Janeiro, Brazil, 1984

[16] Kato, K., Snyder Jr., W.L., Vemuri, S., Papalexopoulos, A. D., Oatts, M.L., Contaxis, G.C., Singh, J., Smith, R.A., Savulescu, S.C., "External Network Modeling -- Recent Practical Experience", IEEE transactions on Pow. Sys., Vol. 9, No. 1, February, 1994, pp. 216-228

[17] Navarro-Perez, R., Prada, R.B., "Voltage Collapse or Steady-State Stability Limit", in Proceedings of the International Seminar on Bulk Power System Voltage Phenomena II ([14] above, pp. 75 - 84)

[18] Oatts, M.L., Erwin, S.R., Hart, J.L., "Application of the REI Equivalent for Operations Planning Analysis of Interchange Schedules", PICA'89, IEEE Trans. on Pow. Sys., Vol. 5, No. 2, May 1990, pp. 547-555

[19] Paternina, E. P., Jaramillo, J. G., Savulescu, S. C., "Operational Experience with the Real-Time Security Assessment System of Empresas Publicas de Medellin", National Energy Conference, June 15-18, 1992, Neptun, Romania

[20] Sauer, P.W., Pai, M.A., "Power System Steady-State Stability and the Load-Flow Jacobian", IEEE Transactions on Power Systems, Vol. 5, No. 4, Nov. 1990, pp. 1374-1383

[21] Savulescu, S.C., "Equivalents for Security Analysis of Power Systems", IEEE Trans. on PAS, Vol. Pas-100, No. 5, May 1981, pp. 2672-2682

[22] Savulescu, S.C., "Design and Testing Criteria for External Equivalents Programs", in Planning and Operations of Electric Energy Systems", Pergamon Press, Oxford, 1986

[23] Savulescu, S.C., Oatts, M.L., Pruitt, J.G., Williamson, F., Adapa, R., "Fast Steady-State Stability Assessment for Real-Time and Operations Planning", IEEE Transactions on Power Systems, Volume 8 T-PWRS, November 1993, pp. 1557-1569

[24] Savulescu, S.C., Leffler, L.G., “Computation of Parallel Flows and the Total and Available Transfer Capability”, Open Access Impact on Energy Scheduling, Pricing and Control, Tutorial Course, PICA’97, Columbus, Ohio, May 16, 1997

[25] Tinney, W.F., Powell, W.I., "The REI Approach to Power Network Equivalents", PICA'77 Conference, May 1977, Toronto, Canada

[26] Van Cutsem, Th., "Voltage Collapse Mechanisms -- A Case Study", in Proceedings of the International Seminar on Bulk Power System Voltage Phenomena II ([7] above, pp. 85 - 102)

[27] Venikov, V.A., "Transient Processes in Electrical Power Systems", English translation, MIR Publishers, Moscow, 1977

[28] Venikov, V.A., Stroev, V.A., Idelchick, V.I., Tarasov, V.I., "Estimation of Electrical Power System Steady State Stability in Load Flow Calculations", IEEE Trans. on Pow. App. Sys., Vol. PAS-94, May/June, 1975, pp.1034-1041

[29] Wu, F.F., Narasimhamurti, N., "Necessary Conditions for REI Reduction to be Exact", IEEE PES Winter Meeting 1979, Paper A 79 065-4

[30] *** "QuickStab Evaluates Steady-State Stability", IEEE Computer Applications in Power, Volume 7, Number 2, April 1994, page 58

[31] *** "Power System Steady-State Stability Monitor Prototype", EPRI Final Report EPRI TR-100799, July 1992

[32] *** "Power System Steady-State Stability Monitor", EPRI Final Report TR-103169, December 1993

[33] *** Electric Power Research Institute -- "Small Signal Stability Analysis Program Package", Version 2.0 User Manual, EPRI EL-6678, Project 2447-1, Final Report, January 1990

[34] *** Electricité de France -- "Special Issue Dedicated to Dimo's Nodal Analysis", Bulletin de la Direction des Etudes et Recherches, Série B, No. 2, 1982

[35] *** "Available Transfer Capability Definitions and Determination", North American Electric Reliability Council, June 1996

[36] *** “GAPP: A General Agreement on Parallel Paths and GIS: An Information System to Support GAPP”, GAPP Project Internal Document, November 1995

[37] “”FERC, “*Notice of Proposed Regulation*”, pp. 363, 1995