Power-system dynamic equivalents: coherency recognition via the rate of change of kinetic energy


Abstract: The coherency aggregation method has proved very successful in the determination of dynamic equivalents of sections of a power system, its main drawback being the extensive computation times required to recognise the coherent groups with full-time simulation. The paper demonstrates the advantages of using the new 'rate of change of kinetic energy' method for coherency recognition in relation to other existing methods. A fault is applied on the power system, an approximate critical clearance time is obtained and machine conditions at that stage are used for recognition. Studies in a large power system are reported. Equivalents are obtained and compared with those produced through full simulation and with the method of the singular points. The effect of fault location on the equivalents obtained is reported. The transient responses of the equivalents produced by the different methods are compared with those of the original system.

List of symbols

\[ RKE = \text{rate of change of kinetic energy} \]
\[ P_{me} = \text{mechanical power of the } i \text{th machine} \]
\[ P_{ei} = \text{electrical power of the } i \text{th machine} \]
\[ p = \frac{d}{dt} \text{derivative} \]
\[ \omega_i = \text{machine speed} \]
\[ \delta_i = \text{internal machine angle} \]
\[ \omega_0 = \text{synchronous speed} \]
\[ n = \text{number of machines} \]
\[ I = \text{vector of nodal currents} \]
\[ Y = \text{admittance matrix} \]
\[ V = \text{vector of nodal voltages} \]
\[ I_i = \text{complex value of injected current} \]
\[ V_i = \text{complex value of nodal voltage} \]
\[ M_i = \text{inertia} \]
\[ a_i = \text{post fault acceleration of the } i \text{th machine} \]

1 Introduction

Considerable interest has been shown, in recent years, in methods to obtain dynamic equivalents of sections of a power system [1, 2]. While computation facilities have increased, so have the requirements for analysis of large-scale systems.

Examples of the need for equivalents arise in both the European and North American power systems. Individual country or state companies require studies to be made taking into account the behaviour of the whole system. These needs arise both in planning and in everyday operation. Often, in planning stages, equivalents of noncritical regions must be obtained to make studies economically feasible. Online analysis must work with equivalents to make fast useful assessments.

The task of obtaining static network-load equivalents is practically solved. Various kinds of equivalents based on Ward and Dimo’s formulations have been proposed and successfully tested in offline and online assessments. Main differences are in the likeness of the power response of the equivalent and the full system. The basic variables compared are active and reactive power flows.

The dynamic equivalent problem is much more complex. Machines interact with each other within areas and across the power network. Control systems are also present, adding new feedbacks and time constants that affect the behaviour of the whole system. It is practically impossible to fully reproduce the behaviour of a whole area of the power system with an equivalent of a much lower order than the actual one, but the search is for the best possible that can match the response of a few variables.

The search for methods to obtain equivalents has been very much related to the search for methods for fast-transient security assessments. The task of assessing if a power system is stable for a given set of contingencies becomes much easier if both a reliable direct method is available and also a reduced model of the system.

The paper reports on how intrinsic energy characteristics of power systems can be used to obtain equivalents, enhancing standard coherency aggregation algorithms. A new method requiring integration over a limited period is proposed, and its advantages over other existing methods are shown.

2 Dynamic equivalents

Three main lines of research are being pursued in the search for dynamic equivalents [1], the three related to similar developments in modern control theory and applications.

Reduced-order dynamic equivalents have been obtained from linear modal analysis of the state equations of the section to be equivalenced. Eigenvalues of the state matrix are analysed and their effect on the system behaviour at specified busbars is checked. Those with insignificant effect are deleted and so is part of the model, reducing its order. The equivalent takes the form of a set of algebraic and differential equations, coupled to the rest of the system at the specified busbars. Unfortunately, these equations cannot be easily associated with a meaningful power-system counterpart. This is the main drawback of the method, although its usefulness, particularly for steady-state stability studies, has been comprehensively tested.

Identification techniques are being proposed for obtaining dynamic equivalents. The basic objective is to identify a reduced-order model of a power system by studying its response to deterministic or stochastic inputs. Different iterative offline identification techniques have been tested. The ultimate aim is directed towards the online environment, where equivalents are searched for with limited boundary measurements of the sections being equivalenced. Although these techniques have proved useful to obtain equivalent parameters of small groups of machines, the procedures
reported in the literature have failed to work when confronted with large sections of a power system.

The third line of research being pursued, and the one that concerns this work, is the coherency approach.

3 Coherency method

The basic old idea behind the coherency method [3] can be clearly understood by looking at different transient stability studies of power systems. Very often, groups of generators tend to oscillate together for a particular fault. Their rotor angle swings are dependent on each other; they evolve together with time. This can be expressed by

$$\delta_i(t) - \delta_j(t) \approx \text{constant } k_{ij} \quad 0 \leq t \leq t_{\max}$$  \hspace{0.5cm} (1)

where \(i, j\) are any pair of generators within the group.

These generators are said to be approximately coherent. If the difference should be exactly constant, they would be exactly coherent in relation to the rotor angles (coherency may also be defined in relation to generator busbar voltages).

Experience has shown that good accuracy is obtained if coherent generators are lumped together into single equivalents. The differential equations of a single machine will represent the whole coherent group. The more exact the coherency, the better the accuracy.

Coherency methods must solve two problems. Firstly, they must provide ways of easily recognising those coherent groups of machines. Secondly, once the groups are identified, they must provide ways of aggregating the parameters of the group into the parameters of the equivalent machine. The effort required and the accuracy obtained will depend on the way the method solves these two problems.

3.1 Coherency recognition

To be able to assess if any two or more machines swing together, the best results can be obtained with a full-time nonlinear transient simulation of the power system. Rotor angles are observed with time and coherent groups recognised. Usually, standard transient-stability programs are modified to include a clustering algorithm that recognises the coherent groups. This modified full transient stability can consume much computer time and storage for large systems. It becomes prohibitive if several studies have to be made to assess coherency in relation to fault location.

Approximate direct techniques have been proposed and tested.

(a) Disturbance measures [2, 4]: Such as admittance distance, acceleration distance or reflection distance (measure of synchronising power) between generators. These measures are evaluated using network and machine information, but no dynamic studies are required. The measures serve as a guide for coherency recognition; they can be used by themselves or as complementary checks with other techniques.

(b) Pattern recognition [4]. Several disturbance measures are combined and used as features for a pattern recognition approach to coherency recognition.

(c) Singular points [5]. Computation of singular points of the post-fault power system provides the closest unstable singular point. This point serves as a representative state of the post-fault perturbed system. If the fault is cleared at exactly the critical clearance time, the system will eventually reach that state. Therefore, that state is used as a guide for recognition. Critical clearance time is understood by power engineers to be the maximum time at which a fault must be cleared to maintain the stability of the system.

Finally, this method uses an admittance distance measure to check coherency.

(d) Lyapunov function [6]. A group of machines is recognised as coherent if their contribution to the total value of a Lyapunov function is small. The system equations are integrated as in any Lyapunov transient study, and the Lyapunov function of the whole system is calculated. The relative value of the function for the group is also calculated and compared.

(e) Linearisation of system equations [7]. A simplified linear model of the power system is analysed using a fast trapezoidal integration algorithm. Swing curves of the linear system are obtained and are used for coherency recognition. A mechanical power input is applied instead of the conventional fault.

(f) Rate of change of kinetic energy. Machine conditions, at a clearance time close to the critical one, are evaluated and serve as a guide for recognition. This is the technique proposed in this paper and its basis is described below.

4 Rate of change of kinetic energy

By studying the different power-system energy forms and their interaction when a disturbance is present, several conclusions may be reached in relation to the system stability. One of them is that the system behaviour as a whole is very much related to its potential energy and its kinetic energy. Some Lyapunov methods formulate theoretical expressions for these energies and use them to assess stability conditions.

Another conclusion can be made relating the system stability to the way the kinetic energy evolves, and, in particular, to its rate of change. When a fault occurs the generators close to the fault speed up, and thus increase their kinetic energy, whereas the rest decelerate, until fault clearance, when a new interaction begins. The rate of absorption or giving up of kinetic energy of each machine plays an important role in defining the final system behaviour.

It can be shown, empirically, in different real-size power systems, that the rate of change of kinetic energy (RKE) at fault clearance time has a maximum negative value around critical clearance time. Practical results support the argument, although exact coincidence between the critical time and the time of the maximum depends on machine loadings, power factors and values of network reactances.

The method proved to give valuable results for transient security assessment, as reported by the authors in Reference 8. Values of clearance times, at which the maximum took place, were within close range of the critical clearance times obtained via simulation. The main deficiency of the method was its unreliability for security purposes. Although values were within much closer range than those obtained with a Lyapunov formulation, some optimistic results were obtained which gave a dangerous assessment for security purposes.

This last restriction is of no importance for the purpose of coherency recognition. The basic advantages of the method can be fully used for system reduction.

4.1 Basic formulation

The kinetic energy of a body of inertia \(I\) rotating at speed \(\omega\) is

\[ KE = \frac{1}{2} I \omega^2 \]  \hspace{0.5cm} (2)

A similar equation can be formulated for a synchronous machine

\[ KE = \frac{1}{2} M \omega^2 \]  \hspace{0.5cm} (3)

But in power-system transient studies, the variable of interest is the departure from synchronous speed rather than the actual speed. Therefore, the kinetic energy of interest is that due to a disturbance, which is expressed by

\[ KE_D = \frac{1}{2} M (\omega - \omega_0)^2 \]  \hspace{0.5cm} (4)
where \( \omega - \omega_0 \) is the speed change caused by the disturbance. The rate of change of that kinetic energy is

\[
RKE = pKE_D = M(\omega - \omega_0)\omega
\]

(5)

The total \( RKE \) for a multimachine system will be

\[
RKE = \sum_{i=1}^{n} RKE_i
\]

(6)

The total \( RKE \) is evaluated in the post-fault system at clearance time. The \( RKE \) reaches an overall minimum, as seen in Fig. 1, which shows the relationship between \( RKE \) and clearance time for two different faults in the 34 machine – 250 busbar system of Fig. 2.

The RKE method obtains critical clearance time within some accuracy margins and it is, therefore, a good candidate for coherency recognition. The simple way in which it can be implemented is an attractive advantage over other methods. Its limitations for security purposes are unimportant here. The coherent groups do not change significantly when the clearance time is permitted to vary around the critical value. Reference 7 goes further in claiming that coherency as a whole is unaffected if the fault clearance time is changed. This claim supports their linearisation of the coherency problem.

The RKE method does not obtain conditions further in time than those obtained immediately after the fault is cleared. But these conditions may be projected to help coherency recognition. In particular, the machine accelerations provide the short-term evolution of rotor angles of the machines after fault clearance.

5 Application of the method

Studies of large power systems show that coherency is not significantly affected by the amount of detail in the modelling.
of the power system in the recognition algorithm. This is also confirmed by Reference 7. Therefore, the simplest models are justified for fast coherency recognition.

The simplest dynamic model of a power system is that described by the following equations:

\[ M_i \rho \omega_i = P_{mi} - P_{ei} \quad i = 1, 2, \ldots, n \]  
\[ p \delta_i = \omega_i - \omega_o \quad i = 1, 2, \ldots, n \]  
\[ P_{ei} = \text{Re} (\dot{V}_i^* \dot{I}_i^*) \quad i = 1, 2, \ldots, n \]  
\[ [I] = [Y][V] \]

which corresponds to a passive network system, with synchronous machines represented as a constant voltage behind a transient reactance, and with inertia characteristics but no damping. Loads are represented as constant impedances. Synchronous speed is assumed not to change substantially.

Therefore, the rate of change \( RKE \) of each machine can be expressed by

\[ RKE_i = M_i (\omega_i - \omega_o) (P_{mi} - P_{ei}) \]

and the total \( RKE \)

\[ RKE = \sum_{i=1}^{n} (\omega_i - \omega_o)(P_{mi} - P_{ei}) \]

For a fault on the system, the rate of change will vary with time. The properties described for \( RKE \) apply for the system conditions immediately after clearance time \( t_c \), that is

\[ RKE(t_c +) = \sum_{i=1}^{n} (\omega_i(t_c +) - \omega_o) [P_{mi} - P_{ei}(t_c +)] \]

and this value reaches a minimum at \( t_c \cong t_{\text{critical}} \).

To apply this method to recognise coherency, integrate the system eqns. with \( a \) and \( b \) coupled with the solution of eqns. \( 8a \) and \( b \), up to the point when \( RKE(t_c +) \) reaches a minimum. Any standard transient stability program serves this purpose; but it should be changed to evaluate the post-fault active power flow \( P_{mi}(t_c +) \) at every time step. This would permit the evaluation of \( RKE \) and therefore the time when it reaches a minimum.

The conditions after clearance time are used for coherency recognition. The machine accelerations provide information on the future evolution of rotor angles. These accelerations are described by

\[ a_i = \frac{1}{M_i} [P_{mi} - P_{ei}(t_c +)] \quad i = 1, 2, \ldots, n \]

After fault clearance, the rotor angle of machine \( i \) will change in proportion to the acceleration \( a_i \). Therefore, comparisons of \( a_i \) can be made for coherency recognition. This is directly related to the concept of acceleration distance given in References 2 and 4.

The term \( [P_{mi} - P_{ei}(t_c +)] \) is obtained when evaluating \( RKE_i \) and is therefore available for the calculation of \( a_i \).

The evolution of rotor angles, between fault occurrence and fault clearance, is also available as a result of the integration and may also be used for coherency recognition.

5.1 Computer programs

The comparison of the new method with the other techniques was performed using a modified full transient stability (MFTS) program and two specially built new programs [9], one using the \( RKE \) method and the second using the singular points (SP) method [5]. This last method recognises coherency by comparing angle differences between the original load-flow solution and the closest unstable singular point. The basic problem is finding that point without having to perform any simulation. Lyapunov transient direct methods are also confronted with this problem [8] and sophisticated searching algorithms have been devised to solve it. To simplify this search, the SP method only pretends to study coherency for faults at generator busbars. Then the assumption can be made that only the faulted machine will separate from the rest in an unstable condition. The SP program utilises an iterative-Newton-Raphson algorithm to find the relevant singular point for coherency determination. Whether the assumption made is valid or not, the iterative algorithm is initialised by considering \((\delta_1, \delta_2, \ldots, \delta_k, \ldots, \delta_n)\) as the starting point, where \( k \) is the faulted machine and \( \delta_i(i = 1, \ldots, n) \) are the values of angles obtained from the original load-flow solution.

The \( RKE \) program does not have limitations on the position of the fault. This program uses implicit trapezoidal integration until the clearance conditions of interest are determined.

Both programs, the \( RKE \) and the SP, work with reduced admittance matrices and sparsity storage. The reduced matrices are obtained from the network information using efficient sparsity routines. When the fault is applied, the \( RKE \) program modifies the reduced matrix using simple diakoptical procedure [10].

Both programs do a coherency selection in relation to angle evolution.

The SP program compares an angle difference with an angle tolerance, the angle difference between the load-flow solution and the determined unstable singular point. The maximum number of machines whose differences are within the angle tolerance, say \( 5^\circ \), are considered eligible for coherency.

The \( RKE \) program estimates the future evolution of rotor angles after clearance time by comparing post-fault accelerations. The relation

\[ \left| \frac{\max a_i - \min a_i}{\max a_i} \right| < 0.50 \]

first proposed by Reference 4, is used to check coherency within a group. It constrains the angle changes, within a group, by constraining the difference between the maximum machine acceleration and the minimum one, within a group.

An admittance distance check is performed in both methods to eliminate machines geographically apart from the groups determined [2]. The constraint imposed is the maximum admittance distance between the machines in a group, with respect to the admittance distance from the group to the study system.

The \( RKE \) program may finally compare the angle differences between the load-flow solution and the determined clearance condition against an angle tolerance. But for all systems studied to date, this check did not alter the coherent groups already recognised.

Following recommendations previously mentioned, both programs work with the simplest models of the power system. Once groups are recognised, aggregation is performed in two steps [11]: a coherency based reduction of generator busbars, where a common new busbar is created and ideal transformers with complex ratios are incorporated to couple it with the old busbars, and, then, a dynamic aggregation of the generating unit models. This last aggregation may include detailed models for the machines and controllers. For the simplest case, it is
just a matter of adding inertia constants and combining transient reactances in parallel, to obtain the equivalent parameters.

Fig. 3 corresponds to the computer-program flow chart for the RKE method. Fig. 4 describes in more detail the block of coherency recognition of groups. This block could be repeated if different studies are to be done for the same case, using different tolerance values.

A full transient stability program was modified (MFTS) to store the machine angle values while the integration is performed. Coherency is then recognised just by checking angle differences between machines within the integration time, with respect to the initial difference. All group combinations that satisfy an angle tolerance are examined. The largest possible groups are chosen as the coherent ones. No admittance distance check is made.

5.2 Results
An actual national power system was used as a test case for comparisons. It has 34 synchronous machines and 250 busbars. A simplified diagram is shown in Fig. 2. The study system was chosen by geographical considerations. It includes machines a to l. Machines 1 to 22 correspond to the external system. Table 1 shows the results of twelve studies to determine coherency with three alternatives, the RKE, the SP and the MFTS. These studies correspond to coherency, determined for a fault at each generator busbar in the study system; studies are ordered by increasing values of inertia of faulted machines. The Table contains the following:

(a) groups determined by each method (Fig. 5 shows graphically some of the groups identified)
(b) computer CPU times for the RKE and SP programs on a CDC 7600 computer
(c) fault-clearance time determined by the RKE method and used to determine coherency with the MFTS
(d) stability condition of the system with that clearance time (stable or unstable in the first swing within the first second of integration).

A general comment can be made in relation to fault location. It strongly influences the coherent groups determined, mainly in its relative position to the machines of large inertia. The smaller the inertia of the machine faulted, the larger the coherent groups. MFTS is the most optimistic in identifying the whole external system as one large equivalent when a low-inertia machine is faulted, even including machines geographically apart. This is the case even when determining coherency with small angle tolerances, because the rest of the machines in the system are not affected; only the small machine faulted drifts away from the rest.

### Table 1: Coherency results

<table>
<thead>
<tr>
<th>Machine faulted</th>
<th>RKE method</th>
<th>Singular points method</th>
<th>Modified full transient stability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coherent groups</td>
<td>CPU time, s</td>
<td>coherent groups</td>
</tr>
<tr>
<td>j</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a, 5, 6), (b), (l, 7)</td>
</tr>
<tr>
<td>c</td>
<td>(a), (b), (c)</td>
<td>1.9</td>
<td>(a, 5, 6), (b), (l, 7)</td>
</tr>
<tr>
<td>b</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a, 5, 6), (b), (l, 7)</td>
</tr>
<tr>
<td>k</td>
<td>(a), (b), (c)</td>
<td>2.4</td>
<td>(a, 5, 6), (b), (l, 7)</td>
</tr>
<tr>
<td>g</td>
<td>(a), (b), (c)</td>
<td>2.3</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>f</td>
<td>(a), (b), (c)</td>
<td>2.1</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>a</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>h</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>l</td>
<td>(a), (b), (c)</td>
<td>2.1</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>e</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a), (b), (c)</td>
</tr>
<tr>
<td>d</td>
<td>(a), (b), (c)</td>
<td>2.0</td>
<td>(a), (b), (c)</td>
</tr>
</tbody>
</table>

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Fig. 3  Program flow chart: RKE coherency equivalents
search two electrically closest generators among those eligible for coherency grouping

search for next two closest generators among eligible

do these generators satisfy the coherency restrictions? (acceleration tolerance and admittance distance)

start forming a group with these generators—make them ineligible

search among rest of eligible generators, the one electrically closest to the group (with respect to the closest machine in the study system) and which satisfies the coherency restrictions

have all generators been checked?

join this generator to the group—make it ineligible

any more eligible?

Fig. 4 Flow chart: coherency recognition of groups

The SP program, when it succeeded, was the fastest of the three in computation time. The closest unstable singular point obtained is most valuable in that it describes conditions far beyond the critical clearance time. The main drawback of the program was that it did not succeed in a few cases. The starting point chosen in the Newton-Raphson algorithm was not useful for the four large-inertia machine cases. In three of them the algorithm did not converge in 30 iterations, and in the last it took 28 iterations. The difficulty arises because for these faults it is not a single machine; but a group that separates from the rest in unstable cases, as was confirmed by the full simulations. This is a major drawback in that some algorithms would have to be included to choose a good starting point to find the relevant singular point. These algorithms would extend the coherency recognition and increase computation time.

The RKE method, although slower than the SP, for most cases, has the advantage of always providing a solution. It still keeps the nonlinear character of the problem; and of all the methods proposed so far, it is the closest in character to the MFTS, without requiring the extensive computation times of the latter. Only a fraction of that time is required, providing at the same time information of approximate values for the critical clearance times. This feature could make it particularly valuable when determining equivalents for security purposes.

To test the equivalents obtained with the three methods, a set of transient stability studies was performed. The simplest model for the power system, as described by eqns. 7a and 8a, was chosen. The equivalents obtained faulting machine i were used. This machine was chosen for all methods, because of the difficulties faced by the SP method when using larger-inertia machines.

The first set of studies done were the classical ones reported by papers on the subject; fault at the machine base of the equivalents, in this case three-phase fault at busbar i. Figs. 6 and 7 show the rotor angle response of machine i (in relation to reference d) for the four cases; full system, system with

Fig. 5 Coherency groups

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RKE equivalents, system with SP equivalents and system with equivalents obtained via MFTS. Fig. 6 is a stable case for clearance time 0.35 seconds and Fig. 7 is an unstable case for clearance time 0.37 seconds. The systems with equivalents give responses very close to those of the full system in both cases.

The second set of studies considers a fault at a line not far away from the machine base of the equivalents. A three-phase fault at point X, as shown in Fig. 2, was considered with the fault and line cleared simultaneously.

Critical clearance times were obtained by repetitive simulations to show how the value is affected by the equivalencing (Table 2). For this particular fault, both the RKE and the SP equivalents behave well, giving critical clearance times close to the real one; although the SP equivalents are optimistic whereas the RKE equivalents are pessimistic. The equivalents obtained with the MFTS are too optimistic. It can be seen because greater grouping was obtained than with the other two methods (refer to Table 1, machine i). This is also reflected in giving a too-optimistic critical clearance time. A more restrictive tolerance of 10° was used, but the grouping is still greater and the critical clearance time is only reduced to 0.27 seconds.

A further test is made of the RKE method. Figs. 8 and 9 show the responses of the full system and of the system with RKE equivalents, respectively, when the fault at X is cleared after 0.26 seconds. Machine d is the reference for rotor angles. The instability is well represented by the RKE equivalents; a group of machines from the external system separates from the study system.

No computer comparison was made of the new method proposed with the linearised method [7], the Lyapunov approach [6] or the pattern recognition [4]. The first one requires linearisation of the power-system dynamic behaviour which the RKE method avoids. The second one may require extensive computation times, if critical-clearance-time equivalents are required. The pattern-recognition formulation includes important post-fault features for coherency recognition, one of which is used by the RKE method. But the application of the method reported in Reference 4 only works with information obtained with the faulted networks at fault occurrence, approximating post-fault features by fault-on ones. Predefined clearance times and projection of post-fault conditions could be done; but tests show this to provide equivalents which are different to the ones obtained with integration up to the critical clearance time. Further tests need to be made, but the RKE method seems to discriminate better than the pattern recognition method; because real evolution of the system is preserved.

When justifying the use of simple models for fast coherency recognition, it was claimed that coherency is not significantly affected by the amount of detail in the modelling of the power system. An example of this is given in Table 3, which gives the coherency groups recognised by the MFTS program for three levels of modelling of the generator machines: simple classical model (voltage behind transient reactance and inertia), fifth-order model (subtransients, d and q axis representation, saturation) and fifth-order model with AVRs. It was advan-

### Table 2: Critical clearance time — fault at point X

<table>
<thead>
<tr>
<th>System Type</th>
<th>Critical clearance time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full system</td>
<td>0.25</td>
</tr>
<tr>
<td>System with RKE equivalents</td>
<td>0.24</td>
</tr>
<tr>
<td>System with SP equivalents</td>
<td>0.26</td>
</tr>
<tr>
<td>System with MFTS equivalents</td>
<td>0.28</td>
</tr>
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### Table 3: Coherency and modelling

<table>
<thead>
<tr>
<th>Machine faulted</th>
<th>Fault clearance time, s</th>
<th>Stability</th>
<th>Level of modelling of generators</th>
<th>Coherent groups recognised</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>0.20</td>
<td>stable</td>
<td>simple classical model</td>
<td>(a, 3), (5, 6, 8, 9, 14), (g)</td>
</tr>
<tr>
<td>d</td>
<td>0.20</td>
<td>unstable</td>
<td>fifth-order model</td>
<td>(a, 3, 14), (5, 6, 8, 9)</td>
</tr>
<tr>
<td>d</td>
<td>0.20</td>
<td>stable</td>
<td>fifth-order model with AVRs</td>
<td>(a, 3, 14), (5, 6, 7, 8, 9)</td>
</tr>
</tbody>
</table>
tageous to use the MFTS for this comparison because it already incorporated detailed modelling of the machines and controllers. A fault at the largest-inertia machine is used for recognition. Similar groups are recognised, not even affected by the different character of stability of the three cases.

6 Conclusions

Although several direct techniques have been proposed to ease the task of coherency recognition of dynamic equivalents, the simplifications made are too crude, the algorithms too cumbersome or the solutions unobtainable. In many cases, transient stability studies of the whole system remain the only useful procedure.

The new method proposed, similar to the transient procedure, utilises intrinsic characteristics of the dynamic process that permit a large reduction of the integration time and, therefore, of the coherency recognition. Only integration up to what is assumed a critical condition is required, nonlinear characteristics are maintained and standard transient stability programs may be used.

Fig. 8 Response of full system
Fault at point X, clearance time 0.26 s.

Fig. 9 Response of system with RKE equivalents
Fault at point X, clearance time 0.26 s.
The tests performed show the new method to be very valuable, with important advantages over other alternative ones.

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8 References