Electric Power System Transient Stability Analysis Methods

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Abstract
In this paper are presented the state of the art of Electric Power System transient stability analysis methods and the results of a hybrid method implementation. There are presented several methods and also a comparison between them. The implemented hybrid method uses indexes to lower the computation time and uses a reduced model equivalent, based on the identification of critical machines, which are responsible for the loss of synchronism.

Index Terms - Critical clearing time, Hybrid methods, Power system transient stability

I. INTRODUCTION

In the last years, due to the spread of electric generation facilities and economic factors, Electric Power Systems operate more closer to their limits [1]. Thus, more than before, it’s of crucial importance the existence of methods to assess the system stability. There are two kinds of stability problems: voltage stability and transient stability [2]. This paper addresses the transient stability.

This paper is organized as follows. In Section II are presented the models used to describe the network components and the network itself. Section III is dedicated to present the state of the art of Electric Power System transient stability analysis methods. The implemented hybrid method is presented in Section IV. In Section V are presented the results of computational tests to which the method was subjected. In the last section, Section VI, are presented guidelines for future works.

II. ELECTRIC POWER SYSTEM MODELLING

In order to study Electric Power System transient stability the models to describe their components should be defined. The components are defined using the classical model, which is valid to time periods up to 2 seconds. [2] It’s also important to define how the disturbances are simulated.

A. Synchronous Generators

Electrically, the synchronous generators are described by a transient reactance $X'_{dl}$ next to an electromotive force (emf) $E'_i$ [2]. So, the $i^{th}$ generator are characterized by the equation

$$E'_i = V_i + jX'_{dl}I_i$$

being $V_i$ the voltage at the generator terminals and $I_i$ the current supplied by the generator.

The rotor dynamics are described using the swing equation

$$\frac{2H_i}{\omega_0} \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_{mi} - P_{ei}$$

where $H_i$ is the inertia constant, $\delta_i$ is the rotor angle, $D_i$ is the damping-torque coefficient, $\omega_0$ is the synchronous speed, $P_{mi}$ is the mechanical power and $P_{ei}$ is the real power [2]. The rotor angle time derivative can be expressed as

$$\frac{d\delta_i}{dt} = \omega_i - \omega_0$$

where $\omega_i$ is the rotor speed.

Usually, the variables that describe rotor dynamics, $\delta_i$ and $\omega_i$, are described using as reference the Centre Of Inertia (COI). The COI is defined as

$$\delta_0 = \frac{1}{M_T} \sum_{i=1}^{m} M_i \delta_i$$

where $M_T$ is the total coefficient of inertia, given by

$$M_T = \sum_{i=1}^{m} M_i$$

and $M_i$ is the coefficient of inertia of the $i^{th}$ generator, which is given by

$$M_i = \frac{2H_i}{\omega_0}.$$
\[\ddot{\alpha}_i = \frac{d\delta_i}{dt} - \frac{d\delta_0}{dt},\]

(9)

\[f_i(\theta_i) = P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{COI},\]

(10)

and

\[P_{COI} = \sum_{i=1}^{m} (P_{mi} - P_{ei}).\]

(11)

B. Transmission Lines

The transmission lines are characterized by the equivalent \(\pi\)-model, thus they are described by the series resistance \(R_L\), the series reactance \(X_L\) and the shunt admittance \(Y_T\) [3].

C. Transformers

Three different types of transformers are considered: the two-winding transformer, the variable transformer and the phase shifting transformer [2].

- two-winding transformer

The two-winding transformer is described by the total series resistance \(R_T\) and the total series reactance \(X_T\), or by the total series impedance \(Z_T\), given by

\[Z_T = R_T + X_T.\]

(12)

The magnetization current is neglected.

- variable transformer

The variable transformer are modelled by an ideal transformer with transformation ratio \(m'\) next to the total series impedance \(Z_T\).

- phase shifting transformer

The phase shifting transformer is similar to the variable transformer but the transformation ratio is complex. So this transformer are described by an ideal transformer with complex transformation ratio \(m'\) next to the total series impedance \(Z_T\).

D. Loads

All the loads are modelled using a constant admittance model [3]. So, a load with real power \(P_{ck}\) and reactive power \(Q_{ck}\), connected to a bus with voltage magnitude \(V_k\), numbered \(k\), is represented by a constant admittance of value \(Y_{ck}\):

\[Y_{ck} = G_{ck} + jB_{ck} = \frac{P_{ck} - jQ_{ck}}{V_k^2}.\]

(13)

E. Network

The network is characterized by an reduced admittance matrix \(Y_{red}\), which is obtained by adding the constant admittances of modelling the loads and the transient reactance of each generator [2]. This matrix is obtained from the equation

\[\begin{bmatrix} I \end{bmatrix} = \begin{bmatrix} Y_{mn} & Y_{mm} \end{bmatrix} \begin{bmatrix} E' \end{bmatrix} \]

\[\begin{bmatrix} 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \end{bmatrix} \begin{bmatrix} V \end{bmatrix},\]

(14)

where \([E']\) is the emf vector, \([I]\) is the current supplied by the generators vector and \([V]\) is the bus voltages vector. After some algebra, the \(Y_{red}\) matrix is defined as

\[Y_{red} = [Y_{mm}] - [Y_{mn}][Y_{nn}]^{-1}[Y_{nm}].\]

(15)

The real power supplied by each generator is obtained using the equation

\[P_{ei} = \text{Re}(E'I_i)\]

(16)

which becomes, omitting the algebra:

\[P_{ei} = E_i^2 G_{ii} + \sum_{j=1 \atop j\neq i}^{m} E_i E_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)]\]

(17)

where \(G_{ij}\) and \(B_{ij}\) are, respectively, the real and imaginary of the \(ij\) positions of admittance matrix that describes the network.

F. Disturbances

The studied disturbances are only three-pole short-circuits with contact to ground near the buses. In the prefault period, the system is in steady state. The disturbance occurs at 0,1 s of the simulation \((t_{def} = 0,1\) s) and it’s eliminated at the clearing time \(t_{cl}\). During the fault period, the disturbance is simulated by adding a large magnitude fault admittance \(Y_{def}\) to the admittance matrix. The disturbance is cleared spontaneously or by turning off one line, which must be reflected in the admittance matrix [4].

III. ELECTRIC POWER SYSTEM TRANSIENT STABILITY ANALYSIS METHODS

There are several methods to study the transient stability of Electric Power Systems. These methods can be gathered in four groups: Numerical Integration Methods, Direct Methods, Hybrid Methods and Artificial Intelligence Techniques.

A. Numerical Integration Methods

An Electric Power System can be described by two sets of equations: a differential set related to the generators and an algebraic set related to the others components [3]. The way these methods study the transient stability of the system is solving, in the time, the two sets of equations mentioned above. These methods offers very good modelling capabilities.

B. Direct Methods

These methods are also called Energy Function Methods, because they are based in comparisons of energy values [5]. More precisely, these methods calculates the energy value at the clearing time and the critical energy value. If the energy value at the clearing time is higher than de critical energy value the system is unstable, otherwise the system is stable.
These methods only require to solve the equations during the fault period, which leads to lower computation times.

C. Hybrid Methods

The Hybrid Methods gather the advantages from the Numerical Integration Methods with the advantages from the Direct Methods [3]. From the first they get the modelling capabilities, whereas from the second they get the fast analysis capabilities.

D. Artificial Intelligence Techniques

These are the newer approach to assess the transient stability of Electric Power Systems [3]. Unlike the previous methods, which are all deterministic, these kind on methods are probabilistic. They are characterized by being necessary to do a lot of simulations before being ready to use. However, when in use, they provide a very fast analysis.

E. Comparison between Methods

Between all the methods presented here, the best results are obtained with the Hybrid Methods and with the Artificial Intelligence Techniques. Due to the simulations that the Artificial Intelligence Techniques require before being ready to use, the Hybrid Methods take advantage when it’s necessary to choose one [3].

IV. Implemented Hybrid Method

The developed hybrid method aim is to determine the critical clearing time for specific disturbances, which are defined by the user. As mentioned above, the disturbances are triphasic short-circuits near the buses, that are cleared spontaneously or by turning off one line. The method is developed in matlab.

A. Data Input

All the data is provided to the program by way of Excel files. It’s necessary to provide data about all the network components and about the disturbances. The program only needs to know the directory where the Excel files are stored, because after loading the files it’s autonomous [4].

B. Prefault Values Computation

The step of prefault values computation includes the solving of a power flow, the modelling of the loads by constant admittances and the computation of initial values of emf’s and mechanical power of the generators [4].

The power flow is solved using the Newton-Rapshon method, which enables to have the voltage magnitude and phase for all the network buses.

The modelling of the loads by constant admittances has been explained above.

The magnitude of emf’s and the value of mechanical power stays constant trough the simulations, due to the use of classical model.

C. Critical Time Cycle

This step is the more complex of the developed hybrid method. It’s started with the numerical solving of the equations that describe the system. The solving is stopped before the total simulation time due to the use of stability and instability indexes. When the numerical solving is stopped, it’s time to find the critical machines cluster. To find that, it’s necessary to use two different criteria, which choice is based in the previously referred indexes. After that the system is reduced to an equivalent machine connected to an infinite bus. This reduced model is studied using the equal area criterion, from which the transient stability margin is calculated. Due to the lack of all the values of power curve of equivalent machine, it’s necessary to model that curve to estimate the remaining values. Based on the calculated values of transient stability margin, a new critical time estimate is made.

- stability and instability indexes

To stop the numerical solving of the equations it’s necessary to resort to two indexes: one of instability (IDCS) and one of estability (IDE) [3]. The first one is computed with

$$IDCS = \sum_{i=1}^{m} f_i^2$$

and a relative minimum in this index corresponds to an unstable situation. The second one is computed using

$$IDE = \sum_{i=1}^{m} \bar{\omega}_i (\theta_i - \bar{\theta}_i^c)$$

where \(\theta_i^c\) is the rotor angle at clearing time, referred to COI. When this index suffers a signal change, from positive to negative, the situation is stated to be stable.

The two indexes are computed at each step of numerical solving in the post-fault period and, when one of the indexes presents the characteristic behaviour, the solving is stopped and the situation is declared stable if it was the IDE index to give the stopping order, or unstable if it was the IDCS index [4].

- critical machine cluster identification

This identification is made resorting to two different criteria, depending on situation’s stability or instability, at an optimal instant of numerical solving which is found trough an index, the IDTO, which is computed with the equation

$$IDTO = \sum_{i=1}^{m} f_i \bar{\omega}_i.$$  

When this index, that is calculated in each step of the post-fault period, reaches an signal change, that moment matches the optimal instant [3].

The criteria, from the two available, to find the critical cluster, is choose based in the situation’s stability or instability: if the situation is stable it’s used an index based in the rotor angles variation; if the situation is unstable, it’s used a method called Critical Machines Ranking (CMR) [4].

The first index is computed, for each generator, using
\[ \mathit{IA}_{\text{COI}} = \sum_{t=t_0}^{t_0+\Delta t} [\theta_i(t + \Delta t) - \theta_i(t)] \]  

where \( \Delta t \) is the integration step. The indexes to all the generators are then sorted in descending order. After that, it’s computed the bigger difference between two consecutive values. The generators above the biggest difference are the critical cluster, the others are the remaining machines [3].

The method used to find the critical cluster, when the situation is unstable, begins with the sort in descending order of all machines rotor angle \( \delta_i \) [6]. Then, one proceeds as follows:

1. pick \( i^{th} \) machine in the decreasing order list from top to bottom in order, which compose subset C; the rest is belong to the remaining machine system, the subset R, where \( i = 1, 2, ..., m - 1 \), being \( m \) the number of generators;
2. calculate for the two systems the COI angle and the difference between them;
3. repeat 1 and 2, until the top \( n-1 \) machines in the decreasing order list have been chosen.

The two subsets with the largest difference between COI angles are the classification wanted. The COI angles for the subsets C and R are computed with the equations

\[ \delta_C = \frac{1}{M_C} \sum_{k \in C} M_k \delta_k, \]  
\[ M_C = \sum_{k \in C} M_k, \]  
\[ \delta_R = \frac{1}{M_R} \sum_{j \in R} M_j \delta_j \]  
\[ M_R = \sum_{j \in R} M_j, \]

and

\[ \delta_{eq} = \delta_C - \delta_R \]  
\[ \omega_{eq}(t) = \omega_C(t) - \omega_R(t). \]

The total inertia coefficient is obtained using

\[ M_T = M_C + M_R \]

whereas the equivalent inertia coefficient is computed using

\[ M_{eq} = \frac{M_CM_R}{M_C + M_R} \]

To fully define the equivalent machine it’s only missing the equations to compute the equivalent mechanical and electrical power. The equivalent mechanical power is calculated using

\[ P_{m\,eq}(t) = \frac{1}{M_T} \left( M_R \sum_{k \in C} P_{m_k}(t) - M_C \sum_{j \in R} P_{m_j}(t) \right) \]

whereas the equivalent electrical power is calculated using

\[ P_{e\,eq}(t) = \frac{1}{M_T} \left( M_R \sum_{k \in C} P_{e_k}(t) - M_C \sum_{j \in R} P_{e_j}(t) \right). \]

- transient stability margin computation

It’s based on transient stability margin values that the critical time estimations are made. The value of transient stability margin \( \eta \) is easily calculated using
\[ \eta = \frac{\delta_{eq}^u}{\delta_{eq}^0} \int_{\delta_{eq}^0}^{\delta_{eq}^u} (P_{e\ eq} - P_{m\ eq}) d\delta_{eq}. \]  

(36)

where \( \delta_{eq}^0 \) is the initial rotor angle value and \( \delta_{eq}^u \) is the rotor angle, bigger than \( \delta_{eq}^0 \), for which the mechanical power equals the electrical power.

Apparently the process to calculate the transient stability margin seems to be easy. However, due to the stop of numerical solving before the total simulation time, the power curve is not fully available. So, it’s necessary to fit the available data in order to predict the missing values.

This fitting is made using two different methods: a trigonometric fitting and a polynomial fitting. In the beginning it’s used the trigonometric one, until the variation between two consecutive estimates is lower than a tolerance \( \varepsilon_1 \). After that it’s used the polynomial one until the variation between two consecutive estimates is lower than a tolerance \( \varepsilon_2 \), time when the process stops.

The trigonometric fitting tries to model the data by the equation

\[ P_{e\ eq}(\delta_{eq}) = \frac{P_{e\ max}}{} \sin(\delta_{eq}) \]  

(37)

where \( \frac{P_{e\ max}}{} \) is the maximum electrical power the equivalent generator can supply.

The polynomial fitting tries to model the data by the equation

\[ P_{e\ eq}(\delta_{eq}) = c_1 \delta_{eq}^3 + c_2 \delta_{eq}^2 + c_3 \]  

(38)

where \( c_1, c_2 \) e \( c_3 \) are constants.

The use of two different fitting rises from the fact that the trigonometric one is strong even with a bad initial critical time estimate but it’s less accurate, whereas the polynomial one is weak with a bad initial critical time estimate but it’s more accurate finding the correct critical time.

- **critical time estimation**

As mentioned, the critical time estimates are based on the transient stability margin calculated values. In fact, it’s is admitted that there is a linear relation between the clearing time and the transient stability margin. So, starting from the available transient stability margin values, it’s possible to estimate a new and more near to the final solution critical time, regarding that a null transient stability margin matches the wanted critical time.

The process is easy to explain. Starting from the current \( (i) \) and previous \( (i - 1) \) iteration values of clearing time and transient stability margin it’s find the line equation that relates that values:

\[ \eta(t_{cl}) = m_\eta t_{cl} + b_\eta \]  

(39)

where \( m_\eta \) is the slope obtained by

\[ m_\eta = \frac{\eta^1 - \eta^{i-1}}{t_{cl}^1 - t_{cl}^{i-1}} \]  

(40)

and \( b_\eta \) is the y-intercept of the line, obtained using (39).

With the line equation available, and setting \( \eta(t_{cl}) = 0 \), the new critical time estimate is made [4].

- **D. Output Data**

As mentioned earlier, the program aim is to compute the critical clearing time for disturbances defined by the user, so the computed value of critical clearing time is available at the program exit. The number of necessary iterations to compute the critical clearing time value is also available at the program exit. This values are stored in an Excel file located in the same directory of the network data Excel files [4].

- **E. Code files**

The code needed to implement the hybrid method is spread by different code files [4]. The kernel of the program is in a file called “TC”. In this file it’s all the code necessary to implement the code except: the code to the power flow, which is in “TC_TE”; the code to find the critical machine cluster and to compute the reduced system, which is in “TC_MC”; the code to compute the transient stability margin, which is in “TC_ME”.

- **V. Computational Results**

The developed hybrid method was subjected to some computational tests, in order to assess its reliability. The tests were done in the CIGRE test network, which has 7 generators, 10 buses and 13 lines [3].

- **A. Computational Tests**

To assess the method reliability were simulated 29 disturbances, which were all three-pole short-circuit with contact to ground near the buses.

- **results**

They were tested 29 different disturbances. The results show that for 23 disturbances the results were correct. For this results, the maximum absolute difference between the critical time obtained with numerical integration methods and the critical time obtained with the hybrid method is 3 ms, or 0.62%.

- **error analysis**

As said above, 23 of 29 disturbances were correctly studied so, it remains 6 disturbances to analyse. The problems identified in these 6 disturbances can be gathered in 3 groups:

1. critical machines cluster identification: the criteria used to identify the critical cluster don’t offer unequivocal results;
2. power curve fitting mismatch: the methods used to fit the equivalent machine power curve are not able to do it correctly, which causes the programme to get locked in an infinite loop;
3. initial critical time estimation: the hybrid method...
only converges if it receives a more accurate first critical time estimate.

**Possible corrections**

For the three error groups detected there are possible solutions.

1. Critical machines cluster identification: the solution is to use other criteria which, together with those already used, offer unequivocal results;
2. Power curve fitting mismatch: the solution may be to use flags, which are turned on when the program are locked, what causes the simulation to be stopped;
3. Initial critical time estimation: the solution can be to try to find an initial critical time estimate using methods like the extended equal area criterion.

### B. Example

This example consist in the study of one disturbance. More precisely, it was a disturbance happening next to bus 2, which was eliminated by turning off line 1. As referred before, the disturbance occurs 0,1 s after the simulation start.

The program was started with an initial estimate of \( t_{cl} = 0,6 \) s. In Fig. 1 is the rotor angle time evolution. The time that simulations last it’s bigger than the required by the indexes, because to better see the evolution, one chose to let the simulation run. As can be seen, the machine 1 are critical, and the others machines belong to the remaining machines groups, which will be confirmed by the critical cluster identifying criteria. It’s also observable that the simulation matches an unstable situation, which will be confirmed by the stability and instability indexes.

<table>
<thead>
<tr>
<th>Machines</th>
<th>Rotor angles ( \delta_i ) [rad]</th>
<th>Difference [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7,012</td>
<td>6,362</td>
</tr>
<tr>
<td>3</td>
<td>0,700</td>
<td>2,855</td>
</tr>
<tr>
<td>7</td>
<td>0,699</td>
<td>2,046</td>
</tr>
<tr>
<td>5</td>
<td>0,666</td>
<td>1,581</td>
</tr>
<tr>
<td>2</td>
<td>0,628</td>
<td>1,367</td>
</tr>
<tr>
<td>6</td>
<td>0,618</td>
<td>1,121</td>
</tr>
<tr>
<td>4</td>
<td>0,600</td>
<td>0,000</td>
</tr>
</tbody>
</table>

After identifying the critical machines cluster, it’s time to compute the reduced equivalent system, which rotor angle time evolution can be seen in Fig. 3. This figure enables to confirm that the situation is unstable.

The transient stability margin is computed using the power curve of the equivalent machine, which can be seen in Fig. 4. It’s also observable the trigonometric fitting, which is the fitting used here because the estimate it’s still far from the final value. It’s interesting that the supplied values of electrical power are negative, due to the expressions used to get the equivalent machine.

The computed value for transient stability margin is \( \eta^0 = -6,7809 \), whose polarity is consistent with the fact that the situation is unstable. As there available only one value of transient stability margin, it’s not possible to do a new estimate so, the clearing time used in the next simulation is...
computed by $t_{cr}^1 = 0.9 \times t_{cr}^0 = 0.54$ s, which leads to a transient stability margin of $\eta^1 = -5.2493$. With this two values of transient stability margin and respective clearing times, it’s possibly to do a new estimate of critical time, which is $t_{cr}^2 = 0.334$. From now on, it’s only repeating the same steps, so there is no need to show them. In Table II, it can be seen the values obtained in each iteration until the difference it’s lower than a tolerance $\varepsilon_1 = 0.01$ s.

![Diagram of CIGRE test network](image)

**Table II**

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Critical time estimate $t_{cr}^i$</th>
<th>Transient stability margin $\eta^i$</th>
<th>Difference $\Delta t_{cr}^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>0.600</td>
<td>-6.781</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.540</td>
<td>-5.249</td>
<td>0.060</td>
</tr>
<tr>
<td>2</td>
<td>0.334</td>
<td>9.293</td>
<td>0.206</td>
</tr>
<tr>
<td>3</td>
<td>0.466</td>
<td>-1.252</td>
<td>0.131</td>
</tr>
<tr>
<td>4</td>
<td>0.450</td>
<td>0.160</td>
<td>0.016</td>
</tr>
<tr>
<td>5</td>
<td>0.452</td>
<td>-</td>
<td>0.002</td>
</tr>
</tbody>
</table>

When the difference it’s lower than the tolerance $\varepsilon_1$, it’s time to change to the polynomial fitting. With the polynomial fitting the first iteration uses the last critical time estimate, i.e., $t_{cr}^0 = 0.452$ s. As with the previous fitting, after the first iteration it’s not possible to do a new critical time estimate, so the clearing time used in the next simulation it’s obtained by $t_{cr}^0 = 0.98 \times t_{cr}^0 = 0.443$ s. In Table III, it can be seen the values obtained in each iteration using the polynomial fitting, until the difference is lower than a tolerance $\varepsilon_2 = 0.001$ s.

**Table III**

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Critical time estimate $t_{cr}^i$</th>
<th>Transient stability margin $\eta^i$</th>
<th>Difference $\Delta t_{cr}^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.452</td>
<td>-0.606</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.443</td>
<td>0.149</td>
<td>0.009</td>
</tr>
<tr>
<td>7</td>
<td>0.445</td>
<td>0.010</td>
<td>0.002</td>
</tr>
<tr>
<td>8</td>
<td>0.445</td>
<td>-</td>
<td>0.000</td>
</tr>
</tbody>
</table>

When the difference is lower than the tolerance $\varepsilon$, the simulation it’s stopped. The critical time was found in 7 iterations. To find the actual critical time it’s necessary to subtract the time when the disturbance occurs $t_{def}$, so the critical time is equal to $t_{cr} = 0.445 - t_{def} = 0.345$ s.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The paper presents a hybrid method to assess the transient stability of Electric Power Systems. This method is able to find the critical time for disturbances specified by the user. The method gathers the Numerical Integration Methods with the Direct Methods. Due to the use of indexes the method is able to stop the simulation before the total time. After the simulation is stopped, the critical machines cluster is identified and a reduced equivalent model of the system is found, which consists of a machine connected to an infinite bus. This reduced model is studied using the equal area criteria, being computed the transient stability margin from which the critical time is estimated.

Although the method presents some wrong results, it was presented several important concepts and started a path to the implementation of this kind of methods.

B. Future Works

As referred in the paper, the developed methods presents some limitations, specifically it was said that the critical machines cluster, the power curve fitting and the initial critical time estimate still need some work on them. So a future work can be to keep the developing of this methods trying to eliminate the limitations.

Another option to future works is trying to insert new functionalities in the method, like disturbances far from the bus, more precise models to describe the components, etc.

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REFERENCES