FAULT CURRENT DC COMPONENT CALCULATION IN MULTI-MACHINE POWER SYSTEM

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Abstract – A calculation method of transient DC component of three phase short circuit current is proposed. Using a multi-machine model system, 4 different methods are compared, which are catenacci, AIEE, and 4 parameters methods together with the proposed method. Among all these four methods the proposed method gives the most accurate result, almost identical wave form of the averaged wave obtained by the post processing of ATP-EMTP results. Compared to ATP-EMTP the proposed method is more convenient because it automatically gives the severest fault case while ATP-EMTP needs several computations.

Main reason of the discrepancies of the conventional methods is based on the insufficient order of the internal models. In contrast to the proposed method, they use only a second order model at most. The usefulness of the proposed method is demonstrated using a test analysis of the saturation of a current transformer. Computing time is also discussed by comparing the results applied to two 10-machines systems and one 30-machines system.

In conclusion, the proposed method is accurate and is ready to apply to multi-machine systems within a realistic computing time. The usefulness of the proposed method is confirmed by this study.

Keywords: transient DC component, short circuit study, three phase short circuit, sub-transient saliency, saturation of CT

1 INTRODUCTION

Short circuit calculation is one of the most important analysis methods in the power system field. In particular, it gives fundamental and essential information in the field of planning of protective devices, and is used in the routine work.

In AC transient analysis, its solution can be described by the sum of so called transient and steady state components. However, the conventional fault calculation treats the second component only, because we need to solve a large differential equation which describes the dynamics of the whole network if we take into account the first component. This was too much time-consuming compared to the case of considering only the second term, which only requires us to execute one-shot computation of a linear equation.

The above stated second term is usually called as "transient DC component" because it takes unidirectional decaying form, and is important because;

- The iron core of fault detection CT of insufficient cross section can be saturated, leading to degradation of the measurement accuracy [18]
- The performance of circuit breakers can be affected

The dynamics inherent in this "transient DC component" is sometimes called "armature dynamics" because it is basically originated from the differential equations describing armature side or grid circuits.

Traditionally, the transient DC component has been treated by the simple calculation schemes such as catenacci's, XR separation (AIEE), and 4 parameters methods [5]. However, it is easily understood that we will need an innovative transient DC component calculation because the improvement in network communication technology will soon enable us to use more and more accurate real time measurement data.

In the above stated situation, much effort has been made relating to this field. Reference [19] proposes an accurate transient DC component calculation method based on frequency response. The equivalent system impedance is modeled in s domain, from which DC component is obtained by integral transform. Reference [11] proposes to incorporate the armature transients into the conventional synchronous machine model for the purpose of studying the effect of "angular back swing" [6]. The authors successfully represented the power grid by algebraic equation while the effect of the armature transient is taken into account by model switching, and the DC component is analyzed together with AC component. The initial value setting in the transient DC component calculation is proposed by [2] and [4], where the decaying time constant is also discussed. However the decaying time constant in [2] and [4] is basically an approximation, and the accuracy might be not sufficient. Reference [17] also uses the same initial value setting as in [2] and [4] and DC time constant is based on X-R separation method.

Meanwhile, the author proposes a fundamental calculation logic [9] which solves the whole simultaneous equation of the grid using the initial value calculated by the logic proposed in [2]. Although the initial value setting in the present paper is as same as in [2] and [4], references [2] and [4] did not discuss how to evaluate the transient DC component waves, merely using the single time constant. The author further studied this transient DC calculation in [1] and [5], where he proposed to solve the differential equation numerically which describes the transient dc component, free from the limitation of using the exponential decay with single time constant. Furthermore, the author extended the theoretical applicability of his proposal to real scale systems and fundamental calculation accuracy in a simple model are demonstrated, while [2] and [4] discussed one machine power systems only. However, The accuracy of this method in multi-machine systems are not yet confirmed.

In this paper, the results of application of this method to multi-machine systems are explained. The author developed a novel calculation code based on the readily proposed logic, and several multi-machine systems are tested. The results are found to be almost identical to those of ATP-EMTP. Also demonstrated in this paper are 1) how we get the severest fault case (the worst fault phase) in the sense of transient dc component, and 2) implication of selection of numerical integration scheme. Improving the numerical stability of the proposed calculation, the author has successfully obtained another 30 machines model system. It is also described how to evaluate the level of CT saturation using the result of the proposed method.

In Chapter 2 the outline of the proposed calculation scheme is explained. Accuracy and its special consideration are discussed and given in Chapter 3 and 4 respectively. In the discussions about accuracy, the results of the proposed method is compared to those of the three methods, namely catenacci, AIEE (X R separation), and 4 parameters methods because these three are the most frequently used in practice even now. In this paper nonlinearity in the grid is ignored and three phases are assumed to be balanced, but the importance of discussing them is briefly stated in the concluding chapter.

2 PROPOSED CALCULATION SCHEME

Usually the target time zone of the transient DC component calculation is about 5 cycles after fault, in which CT saturation and trip performance of circuit breakers are discussed. The transients observed at the instant of fault clearance and reclosing are also important [4] but are not studied here. Here, the target phenomenon is so fast that we do not need to consider mechanical dynamics and controllers of the generator. Therefore each grid component including load can be treated as constant impedance.

2.1 Differential equation

As stated in Introduction, we need to solve the simultaneous equation (the right hand side is set to be zero) to get the transient DC component. The generator is modeled merely by the series combination of R (armature resistance) and X_2 (negative phase reactance) as explained in [8] and [15].

The differential equations in the proposed calculation are as follows.

$$\begin{aligned} &L_i \frac{di_i}{dt} + R_i i_i = v_{if} - v_{it} \\ &C_j \frac{dv_j}{dt} = i_j \\ &\sum_{k \in S(j)} \text{sgn} \cdot i_k = 0 \end{aligned} \quad (1)$$

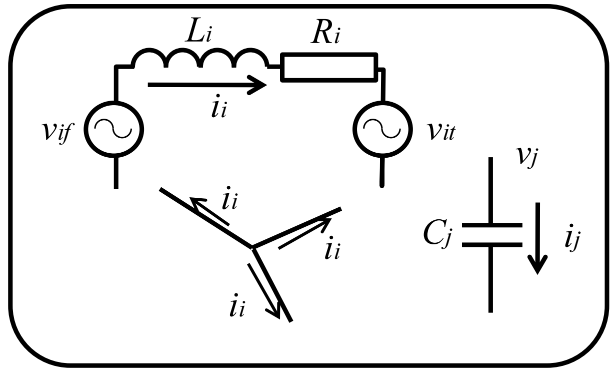


Figure 1: Representation of the system.

They are voltage equation of branch i (capacitive branches representing line charging are not included), voltage-current relation of capacitive branch j, and KCL equation for node k respectively. They are depicted in Fig. 1. It is assumed that all load components and the internal impedance of generators are readily represented by their corresponding impedance. Each symbol stands for;

L_i : positive phase sequence inductance of branch i
i_i : current in branch i
R_i : resistance component of branch i
V_{if} : voltage of the "from" node of branch i
V_{it} :voltage of the "to" node of branch i
C_j :positive phase sequence capacitance connected to node j
i_j : current flowing across C_j
S(j) : the set of the branch connected to node j
sgn : sign function which takes -1 and +1 if the direction of the corresponding branch is outward or inward respectively

The right hand side terms of the above equation (driving voltage terms) are noting but the internal voltage of the sources and all other variables in the right hand side of (1) can be treated as unknowns. In the proposed calculation scheme, the equation is numerically integrated with all these internal voltage of the sources set to be zero.

2.2 Initial value setting

As discussed in [2], the initial values used in the transient DC component calculation should be the difference between two values, one of which is the instantaneous value of the steady state solution of (1), and the other is the instantaneous value at the instant of fault. Because the steady state fault calculation can be done by conventional way, initial value setting is easy.

As widely known, the magnitude of DC component depends on the initial phase at the instant of fault occurrence. In the newly developed calculation code, the worst fault phase (timing) is automatically obtained. Because the worst timing for one branch current is not necessarily the worst for other branches, this procedure is done for one predefined designated branch. This is done by the following simple procedure;

1) calculate initial current i_o by load flow calculation

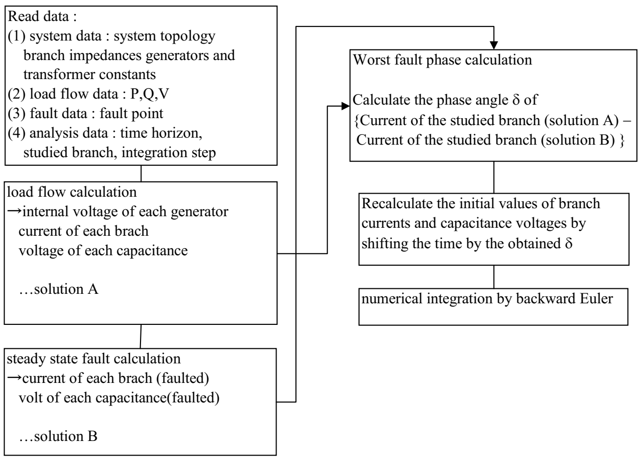


Figure 2: Flow chart.

2) calculate steady state fault current i_f by the conventional fault calculation

3) take the angular phase δ of the difference vector between 1) and 2) i_o - i_f. δ is the worst fault phase

2.3 *Flowchart of the proposed calculation*

Fig. 2 shows the flowchart of the proposed method. Initial load flow calculation (the solution of which is "solution A" in Fig.2) and steady state fault calculation (the solution of which is "solution B" in Fig.2) are done first. Next the differential equation of the simultaneous form (free system) is numerically solved taking the difference of these two as its initial value. Here fault timing is so adjusted as to maximize the initial value of the designated branch.

3 NUMERICAL EXAMPLE

3.1 *Calculation Condition*

IEEJ WEST 10-machine system model shown in Fig. 3 is used as a test system for the verification of the proposed method. The constants are as summarized in Table 1. Three phase fault is assumed to occur at Points A (Case 1), B (Case 2), and C (Case 3). In Case 1 and 3, the designated branch (written in 2.2) is a-A and c-C respectively, whereas in Case 2 two branches are selected as its designated branches respectively. Fig. 4-6 show these branch current in their corresponding cases, compared with the results of ATP-EMTP. In ATP-EMTP computation, the fault timing was gradually changed by the minimum time step 0.1msec and the most severe (DC component is biggest) case is chosen.

Line	length	R(%)	X(%)	B/2(%)
every tie line (horizontal)	100km	0.21	6.3	12.2
every vert. line except from G8	50km	0.11	3.15	6.1
vertical line from G8	100km	0.21	6.3	12.2
transformer of G1		0	0.93	0
transformer of G2-G7,G9		0	1.4	0
transformer of G8		0	2.8	0
transformer of G10		0	0.47	0

Base capacity : 1GVA

Table 1: System parameters.

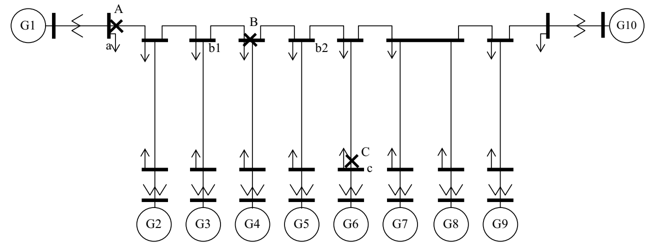


Figure 3: IEEJ West 10-machine system model.

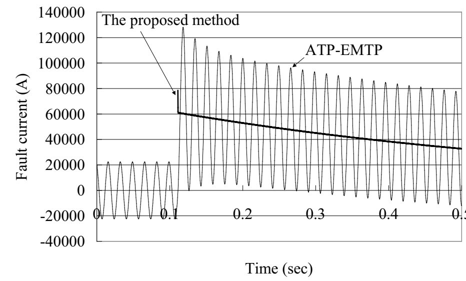
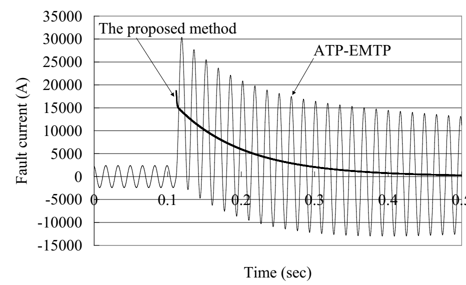
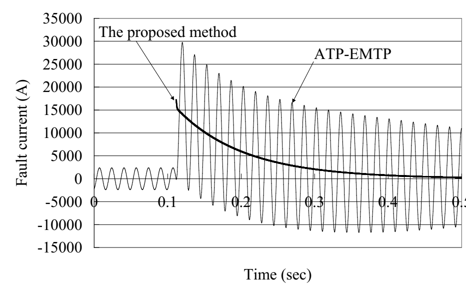


Figure 4: Result of Case 1 (Current from G1).



(a) Fault current from Node b1



(b) Fault current from Node b2

Figure 5: Result of Case 2.

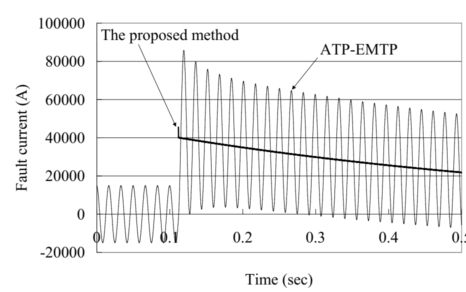


Figure 6: Result of Case 3.

From these figures it can be easily observed that the obtained waves take the average value of the instantaneous current value obtained by ATP-EMTP. It gives DC component of the transient current successfully. Much effort has been made how we can eliminate dc and harmonic component in the fault current for the purpose of accurate evaluation of fundamental component [16], but here AC component is eliminated and DC component is detected. For this purpose the authors used a simple moving average calculation for one cycle.

From these three cases observed are;

1) In Cases 1 and 3, the assumed fault occurs near generators, which means these cases are dominantly important in selection of protective devices of the corresponding generators. The obtained fault current is determined solely by L and R component of the branch between the generator and the fault point. It shows the typical exponential decay and its decaying time constant is comparatively long.
2) In Cases 1 and 3, ATP-EMTP wave tells us that the AC component decays fast because it is greatly affected by the change in generator reactance. However, the DC component does not decay so fast because the effective reactance is constant. As a result so called zero-miss phenomenon lasts for more than 0.1 sec
3) Case 2 is the case where the fault occurs at the center of the system, far from generators. Therefore the contribution of the reactance change in the generators is small, leading to the slow decay of AC component. DC component does not take a simple exponential decaying form because it is fed by several generators.
4) In all cases fast DC decays are observed immediately after fault in the proposed method.

For the further accuracy verification of the proposed method, the ATP result is postprocessed to get DC component. This is shown by the solid line in Fig. 7, where dashed line, the result of the proposed method, is compared. These two are almost identical but the post processing of ATP-EMTP result does not completely reject oscillatory component. In ATP-EMTP run, the time step width in numerical integration cannot be taken so large as in the proposed method, leading to longer computation time. Moreover, the proposed method needs only one computation to get the severest case, which is another merit over ATP-EMTP based analysis.

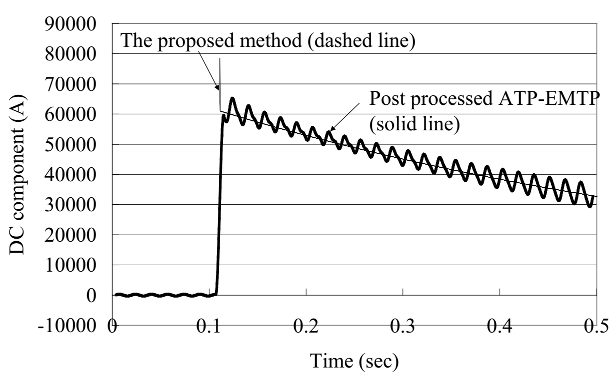
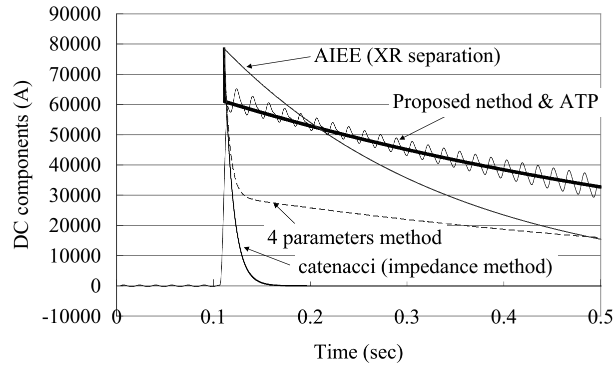
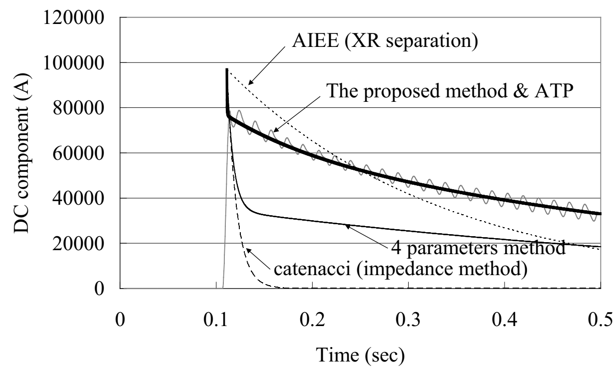


Figure 7: Comparison between the proposed method and the resultant wave of the post process of ATP-EMTP.



(a) Fault current fed from the local generator G1



(b) Total fault current

Figure 8: Comparison of the calculation methods.

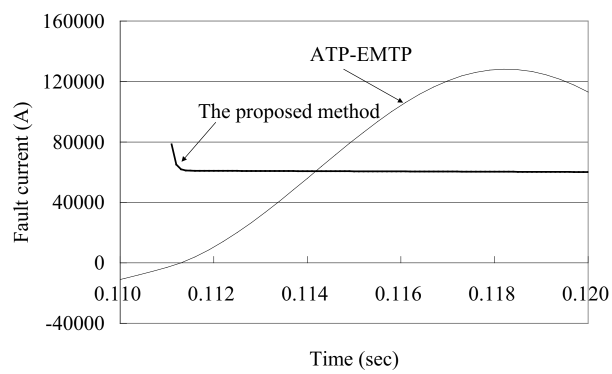


Figure 9: Very fast transient of DC component.

3.2 Accuracy

Accuracy of the proposed method is compared to that of catenacci's method, AIEE method, and four parameters method [5] using Case 1, in which the number of DC components are limited and certain level of accuracy can be expected. Fig.8 shows the result together with the post processed ATP-EMTP wave stated above, which is same as Fig.7. Fig.8 (a) shows the current from G1, same as in Fig.4, whereas (b) shows the total fault current, sum of the two currents flowing from the left (G1) and the right (system). As can be observed from this figure, catenacci's method accurately calculates the fast dynamics immediately after the fault. It is, as written in [5], because the precision of catenacci's method becomes better in high frequency domain. However its DC component quickly decays and eventually disappears around 0.04 sec due to the essential limitation that only one time constant can be represented.

On the other hand AIEE (XR separation) method describes overall DC current exactly but its accuracy is not enough. This can be explained by the fact that this method approximates the circuit response at zero frequency. The four parameters method gives wave almost identical to catenacci immediately after the fault, while it gives current near AIEE method in the latter time zone.

The mechanism of occurrence of the fast initial transient stated before can be explained by paying attention that we have local load P+jQ = 12.0pu + j 2.44pu between G1 and the fault point A, whose equivalent time constant is L/R=0.00054sec, almost identical to this transient. In Fig. 8 depicted is the magnified wave obtained by the proposed method compared to the result of ATP-EMTP. On the other hand, the slow decay which dominates the total wave in Fig. 8 has time constant 0.64sec, which can be physically interpreted to be the dynamics causing by G1 and the associated transformer.

Summarizing all these it can be concluded that the proposed method is far more accurate than these three conventional methods, and gives the true averaged waveform of the result of ATP. Compared to ATP, the proposed method does not need several computation to get the severest case, and has advantage in the sense of computing time because the resultant wave is very smooth, which implies the longer step width can be used.

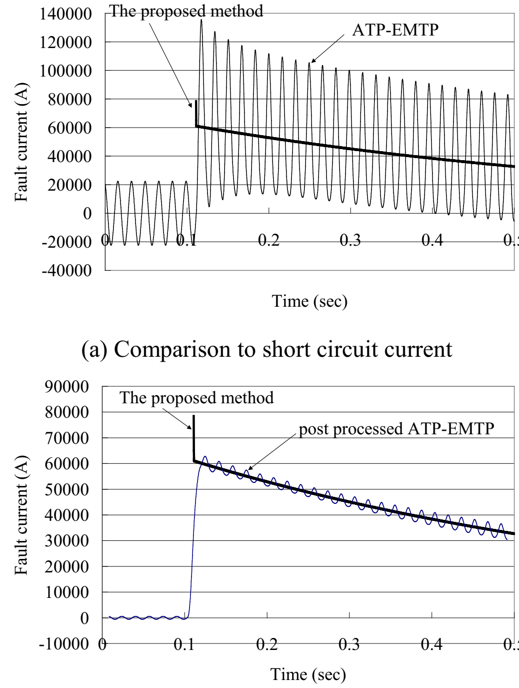
4 DISCUSSIONS

4.1 Effect of Sub-transient Saliency in Generator

In synchronous generators their d and q axis sub-transient reactances are sometimes not the same [14] (sub-transient saliency). In this case voltage and current will have harmonics or deformation even in the case of three phase fault [12]. Because the proposed method is based on the simple assumption that generators are modeled simply as R-L element, the effect of this sub-transient saliency upon the accuracy needs checked.

Case 1 is used again but G1 (X_d"=X_q"=0.25pu) is replaced with a new generator which has sub-transient saliency (X_d"=0.182pu , X_q"=0.4pu) but is identical to G1 in all other points. It has the same negative phase sequence reactance X_2= $2X_d$"X_q"/(X_d"+X_q"), and the DC component given by the proposed method is same as before. Fig. 10 (a) gives the result compared with that of ATP. Wave deformation is clearly observed in the result of ATP. The resultant DC component given by the proposed method might look smaller than the average of ATP wave here, but taking the moving average of ATP result becomes almost identical to the proposed method as shown in Fig. 10 (b).

As shown above, the proposed method can be applied to the cases with sub-transient saliency. It can also be stated that the theoretical derivation given in Appendix of [15] is confirmed numerically by this study.



(a) Comparison to short circuit current

(b) Comparison to the averaged wave form

Figure 10: Effect of Sub-transient Saliency.

4.2 Application to the Study of CT Saturation

As explained in Section 2, one of the most important application field of this calculation is the study of CT saturation. In case of large DC component, the magnetizing admittance might increase, leading to the trouble that the increase in the primary (grid) side current does not affect the secondary side current. It directly causes discrepancy between the real grid current and its measurement. If the measured current magnitude does not reach the minimum criterion for triggering protection, the circuit breaker does not function, a serious problem about grid protection. In this sense transient DC component calculation needs to give accurate evaluation of the secondary current of CT.

The CT measurement system depicted in Fig. 11 is assumed, where its saturation characteristics are also shown. Hysteresis is not considered here because this makes analysis far simpler than considered but does not give any serious error. Most of the former works followed this simplification [18][20]. Three cases are compared in which the primary current is given by the results of ATP, the proposed method, and the four parameters method (the most accurate among the three conventional methods treated in this paper). They are shown in Fig. 12, where the primary current is converted by the winding ratio 5000. As can be easily seen in Fig. 12 (a), the secondary current is different from the primary due to the CT saturation. Because this result is obtained by ATP, it can be treated as almost reality. However, as shown in Fig. 12(c), the conventional method gives an incorrect conclusion, in which the secondary current accurately follows the primary side. On the other hand, the proposed method will give a right decision as shown in (b) In the studied case shown here, the magnitude of the short circuit current is comparatively small, leading to the result that the time to initiate saturation is rather long. The proposed method has been applied to other cases in which the short circuit current magnitude is larger, and it successfully evaluated the saturation.

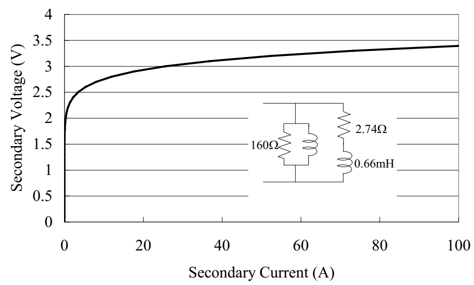
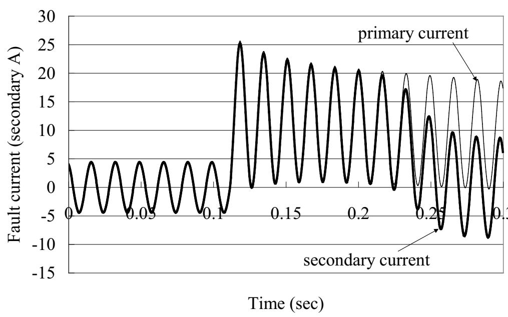
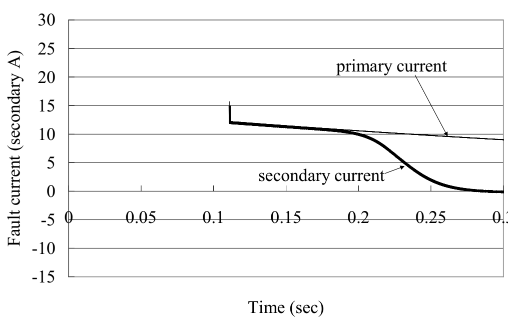


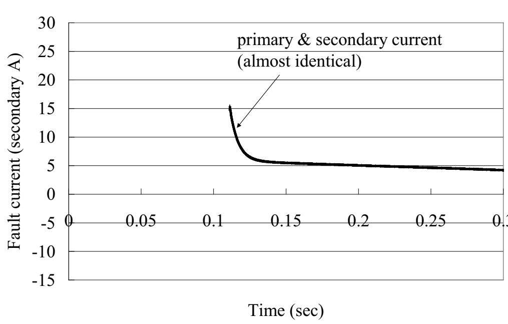
Figure 11: Saturation and Circuit of CT.



(a) ATP-EMTP



(b) Proposed method



(c) 4 parameters method

Figure 12: Comparison on the effect of CT Saturation.

Model system	Nodes	Branches	Time (sec)
WEST-10	27	42	0.953
EASTT-10	47	100	1.750
WEST-30	115	129	11.609

(CPU) Intel CORE(2) 2.13GHz 504MByte

Table 2: Computing Time.

4.3 Computing time and other effects

The developed computer code was applied to several standard system models of IEEJ. The target phenomenon to analyze is 0.5sec, and the integration time step width is 0.0001sec. The result is summarized in Table 2. In all cases computing time is realistic. In calculation of the first system (27 node system) computing time by ATP for one case is 0.593sec, which is a little faster. However, as explained before, in case of using ATP users need several trials to reach the severest case, and the total time will become longer.

Actually the computing time by the proposed method will be able to become shorter, because the linear equation solver is not optimized. This study will be another subject of great importance.

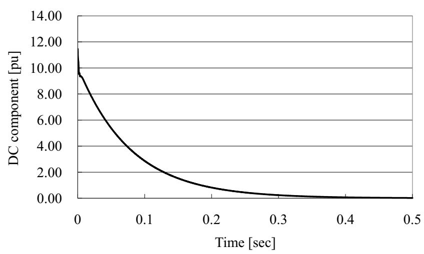
Moreover, the computing time can become shorter if the time step width can be taken longer without question. In this sense it is important that the proposed method uses so called backward Euler's method for the numerical integration, very stable and gives flexibility in selecting appropriate integration step width.

For the convenience of readers, typical results obtained in other sample systems are shown in Fig. 13. As shown in Fig. 3, West 10-machine system has a radial form. However, East 10-machine and East 30-machine systems take a loop form. 1.0 pu in the following figures corresponds to 3.266kA. It is observed that the proposed method successfully gives transient DC component in various systems of structures and scales with high numerical stability. In (a) and (b) high frequency component is observed immediately after the fault, but soon disappears. It is suppressed by the numerically stable backward Euler's method as stated in the previous paragraph. Here, in all cases time step is h=0.0001sec.

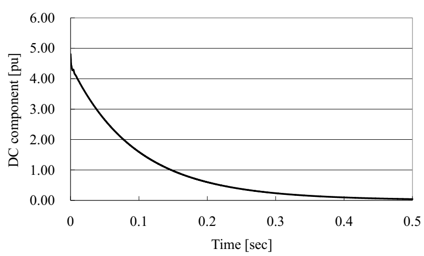
In this sense, it can be said that the author should have used a longer time step width in (a) and (b). Therefore, these two systems are re-calculated using a longer time step. The new results are shown in Fig. 14. It is observed that the initial oscillation is suppressed keeping the overall wave shape unchanged.

It is true that real power systems often have much more nodes, branches, and machines. However, as the electrical distance from the fault point becomes longer, the contribution to the transient DC component becomes smaller. It means that it will not give a big influence even if we reduce the whole system in which its remote part is modeled by the equivalent voltage source together with a short circuit impedance. We need another study to clarify the validity of this kind of system reduction in the sense of accuracy of transient DC component calculation. It is outside of the scope of this paper.

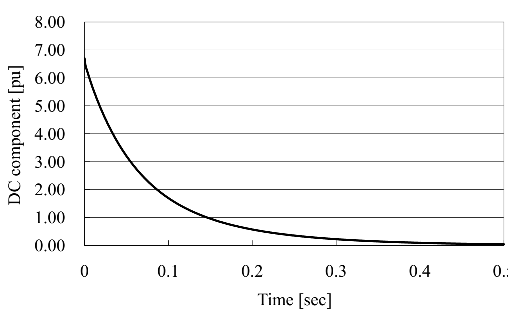
Also important in a realistic sense is the user-friendliness of the program. If the I/O data structure is compatible with a widely used standard software, more users are expected, and the developed program will be more improved. The author is now trying to make a converter system among the well known systems and the proposed method.



(a) example of the result in East 10-machine system



(b) example of the result in West 30-machine system

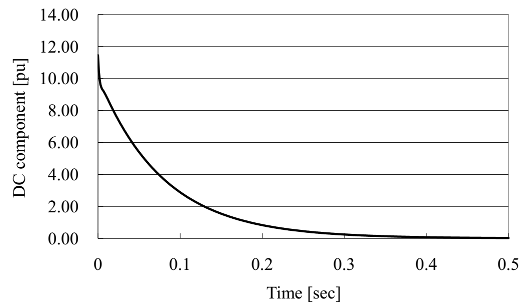


(c) example of the result in East 30-machine system

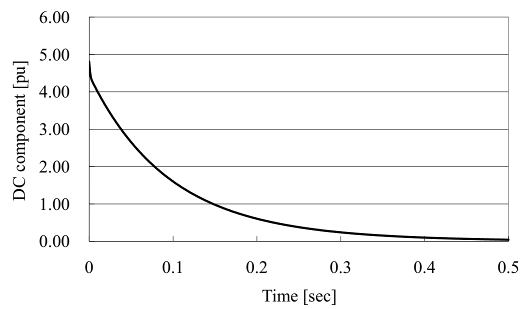
Figure 13: Typical examples of the result of the proposed method in other sample systems.

5 CONCLUSIONS

This paper proposes a new transient DC component calculation method for fault current. Starting from the ordinary load flow calculation and fault calculation, detailed transient response of fault current DC component is clarified. In the proposed method, the real transient of DC component is accurately calculated in which



(a) the result in East 10 with h=0.001sec



(b) the result in West 10 with h=0.001sec

Figure 14: Influence of time step selection on the result.

many factors with various time constants are involved such as the fast initial decay with millisecond level and the slow dynamics originated from generators and transformers.

Accuracy of the result is confirmed by comparison to ATP-EMTP. The proposed method gives almost identical waves to the DC component obtained by post processing from ATP results. The required computing time is shorter than ATP owing to the newly developed function which automatically finds the severest fault timing. Thanks to so called backward Euler's method, the proposed method is expected to be numerically robust or stable even in the case of long integration step width. In addition, it is confirmed that the proposed method can give accurate result even when considerable difference exists between d and q axis sub-transient reactance. The merit of the proposed method is demonstrated paying special attention to its application to CT saturation problem. Computing time is also discussed.

Another important aspect of transient DC component calculation is its applicability to the cases of asymmetrical fault and nonlinear grid. Basically the proposed method has a good potential to be directly applied to asymmetrical case, where the only modification will be usage of multiple phase formulation. However, application to the nonlinear grid needs some technical innovation such as the perturbation series model [21], which mathematically transforms the nonlinear system to the set of linear systems. In near future the author is going to study these issues.

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