Inrush Currents of a Large Step-Up Transformer and Means for Their Reduction

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Abstract - **The highest inrush currents of a large 765kV step-up transformer lead to significant voltage depression and distortion at the 765kV bus especially at a reduced level of short-circuit power. The possible countermeasures are closing resistors, synchronized closing, prevention of residual flux and combinations of those measures. The influence of those means has been analysed on the basis of a transformer model comprising hysteresis and residual flux.**

Keywords: Transformer, Inrush, Modelling, ATP, Closing Resistors, Synchronized Closing.

I. INTRODUCTION

In Guri Hydro-Power Plant of EDELCA the use of circuit-breakers (generator circuit-breakers) at the generator side of the step-up transformers would grant a multitude of technical and operational advantages.

The use of those generator circuit-breakers implies on the other hand energization of the unloaded step-up transformers from the high-voltage side. Depending on the instant of closing this may cause inrush currents exceeding the rated transformer current. Although all transformers are designed for withstanding their inrush currents other effects linked to high inrush currents as voltage distortion are less desirable.

This paper presents the results of a study about the worst-case inrush currents of the largest step-up transformers in Guri Hydro-Power Plant when energized from the high voltage side as well as their consequences on the height and shape of the bus voltage. The influence and limits of various means for reduction of the inrush currents as closing resistors and synchronized closing are also given in the paper.

The following criteria have been applied when preparing the study:

- worst case configurations and worst case assumptions have been chosen
- realistic, physically correct models have been employed for the simulations
- all models have been checked for correct steady state behaviour.

II. INPUT DATA

The largest step-up transformers at Guri Hydro-Power Plant i.e. the 3 x 268.5MVA, 765/18kV, single phase units have been selected for the study. The energization of such a transformer at unfavourable instants leads to the highest reactive power absorption and hence to a considerable voltage depression and distortion in the high voltage system. The selection of this transformer (unit 12) represents already part of the worst case conditions.

Step-up transformer data (unit 12):

3 single-phase units, YNd1, 60Hz
3 x 268.5MVA

rated voltages	:	765/√3 : 18kV
short circuit losses	:	690kW / 1-phase unit
no-load losses	:	101.3kW / 1-phase unit
short-circuit reactance	:	0.14p.u.
no-load current	:	0.116%

H.V. system:

rated voltage	:	765kV, 60Hz
short-circuit power	:	30.25GVA

III. MODELLING

The given step-up transformer data are not completely sufficient for the simulation of the inrush currents. Due to the fact that transformer manufacturers world-wide use similar magnetic materials and employ similar design concepts it seems to be admissible to use characteristic and typical data regarding the magnetic circuit of the step-up transformer in question. This is also in line with recommendations given in the literature [1, 2, 3].

The program used for the inrush simulations is ATP [4]. The step-up transformer is modelled 3-phase based on the single-line diagram of Fig. 1. The "saturable transformer component" has been combined with the "pseudo-nonlinear hysteretic inductor component" of [4].

As in reality the h.v. winding resistance has a damping effect on the inrush current. The vector group YNd01 is correctly reproduced by the l.v. side connections; the neutral of the h.v. windings is grounded. The winding resistances have been adapted to

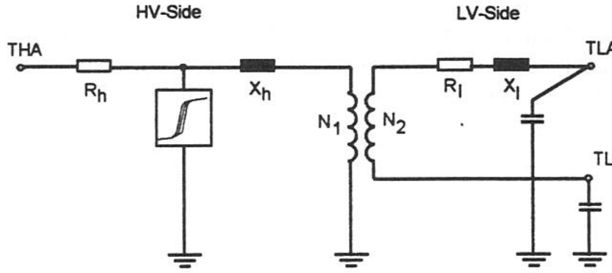

Fig. 1. Transformer model, single phase

correspond to the short-circuit losses of 3 x 690kW, i.e. $R_h = 0.947\Omega$, $R_l = 0.00153\Omega$.

The decisive data regarding inrush current is the magnetic characteristic of the transformer. Based on typical transformer manufacturer data the ratio of kneepoint induction to induction at rated voltage is 1.24. The air core reactance (in the totally saturated range of the magnetic characteristic) has been chosen to be $2 \times L_{short\text{-}circuit,\ total} = 0.57H$ [1, 3].

From those data and taking into account the no-load losses of 3 x 102kW (corresponding to the hysteresis area of the flux - current curve times rated frequency) and a rms-value of 0.7A of the no-load current the simplified flux - current curve of Fig. 2, referred to the h.v. side can be deduced.

With this curve the residual flux can be varied in the range of ± 0.9p.u. Basically it is determined by the preceding opening operation. Practically it is very difficult to determine the actual value of the residual flux however [3]. According to the recommendations of a renowned transformer manufacturer a maximum value of 0.68p.u. for the residual flux has been chosen.

Based on experimental experiences showing that the sum of the residual fluxes is about zero in the 3 phases [5] the worst case scenario with opposite polarities and maximum residual flux in 2 phases and zero residual flux in the third phase has been chosen.

Obviously the maximum inrush current occurs in that phase where - starting with the closing instant - the

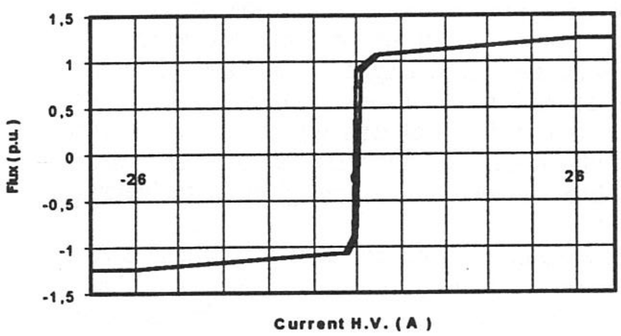

Fig. 2. Saturation and hysteresis curve of step-up transformer referred to h.v. side

flux i.e. $\int u dt$ shows the same polarity as the residual flux. In the simulations this is always phase A. That means at positive residual flux in phase A the voltage in phase A at the closing instant passes through zero from negative to positive polarity.

Without residual flux the highest inrush current is caused by closing at any voltage zero crossing.

The transformer model according to Fig. 1 and 2 and the above data has been checked under no-load and short-circuit test conditions. The peak value of the no-load current is 1.5A, the rms-value is 0.7A, which corresponds to 0.116% of the rated current. The energy absorbed by hysteresis is 10.2kWs/phase for 0.1s, i.e. 102kW no-load losses.

Short-circuit testing of the transformer model yielded the correct rated winding currents of 607.9/14916A at 14.8% rated voltage. The corresponding short-circuit losses at those conditions amounted to 690.6kW/phase.

The 765kV-system has been modelled by reactances and resistances of the positive and zero-sequence system with typical ratios:

$X_1/R_1 = 25$, $X_0/X_1 = 2$, $X_0/R_0 = 15$

A capacitance of $0.33\mu F$ at the 765kV bus has been deduced from TRV requirements.

IV. CASES ANALYZED, RESULTS, DISCUSSION

1. Basic case

For all simulations under this paragraph worst case conditions as described above and simultaneous closing of all three phases have been assumed.

Fig. 3 shows the most unfavourable case, i.e. residual flux of +0.68p.u./-0.68p.u./0p.u. in phases A/B/C and zero crossing from negative to positive polarity of phase voltage in phase A (closing angle = -90°el.). The closing instant is at 16.66ms, i.e. the voltages during the first period are unaffected.

After closing a significant voltage depression is visible, especially in phase A. As expected the inrush current in phase A is maximum with a peak of 3.59kA.

The polarity combination +/0/- has also been checked and found to yield the same results.

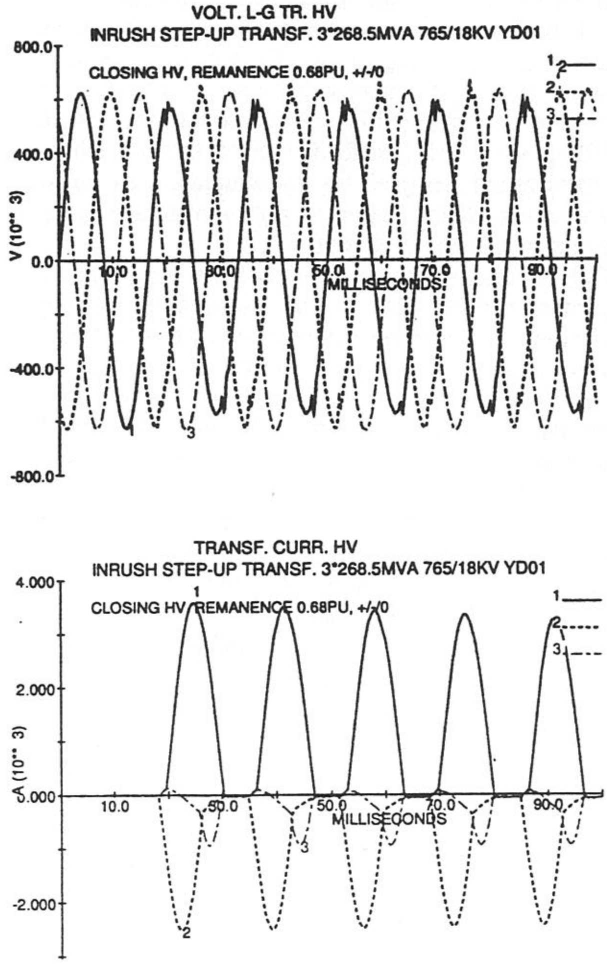

Fig. 3. Bus voltages and inrush currents

To be sure that Fig. 3 corresponds to the absolute maximum of the inrush current, closing around this instant has been analyzed too up to ±15°el. in steps of 5°el. for the polarity combination +/-/0.

The inrush current peaks in phase A exhibit a very flat maximum around -90°el. closing angle.

Another interesting item is the influence of the height of the residual flux on the inrush current peak, all other parameters remaining unchanged.

This correlation is given in Fig. 4

The inrush current peaks grow linearly with residual flux starting from $\hat{I}_{inrush}$ at residual flux = zero. For the selected residual flux of 0.68p.u. the inrush current peak is twice that of zero residual flux. This shows already the potential of avoiding residual flux.

The decay of the inrush currents is rather weak. Fig.5 has an extended time scale. The time constant is about 0.8s.

The maximum inrush peak value of 3.59kA has to be compared to the maximum asymmetric peak short-circuit current of the transformer (3-phase short-circuit at the 18kV-side), which amounts to 9.6kA. Certainly the maximum inrush peak does not jeopardize the transformer.

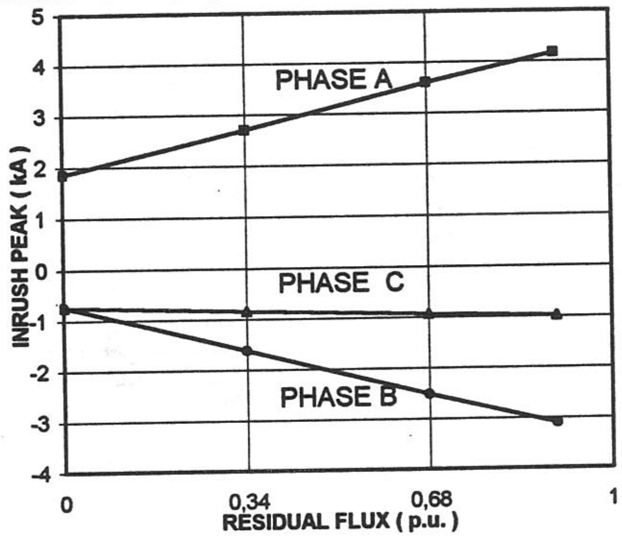

Fig. 4. Inrush peaks as a function of residual flux

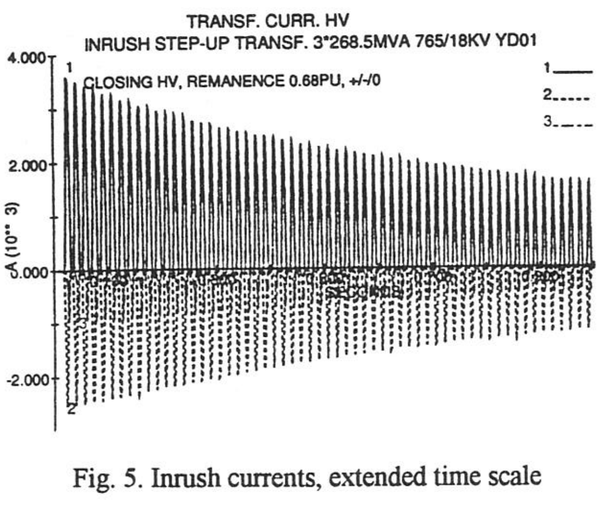

Fig. 5. Inrush currents, extended time scale

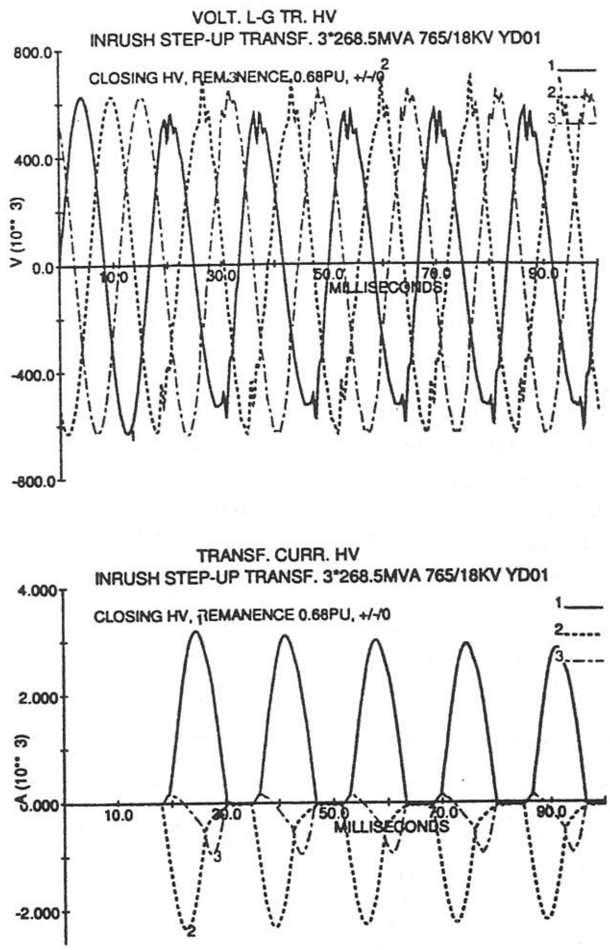

Fig. 6. Bus voltages and inrush currents at 50% short-circuit capacity

Apart from the mechanical effects of the inrush current (transformer ageing) the voltage deformation and depression could be of concern regarding power quality.

Obviously voltage depression and total harmonic distortion (THD) is more pronounced if the source is weaker. Fig. 6 corresponds to Fig. 3, except short-circuit power which is now 50%.

A comparison of those 2 cases is given below.

Short-circuit power S_{sc} / GVA	$\hat{I}_{inrush}$ kA	THD_A %	Volt. depress. $U_{A,\ 1st\ per.}$ p.u.	Fig.
30.250	3.59	5.09	0.93	3
15.125	3.21	9.01	0.89	6

At 50% short-circuit power the maximum inrush peak is about 10% smaller, the total harmonic distortion however has almost doubled. Also voltage depression in phase A is in a range where sensitive equipment could be affected. The dominant harmonics are the second and third ones, but even high order harmonics as order 14 can reach comparatively high amplitudes.

2. With closing resistors

Closing resistors of 1000Ω/phase are used for the 765kV line circuit-breakers in Guri Hydro-Power Plant. They normally can be added also to an existing circuit-breaker of the same make e.g. to the 765kV transformer circuit-breakers. This is the reason why this alternative has been analyzed, maintaining also the resistor value of 1000Ω. A typical resistor insertion time of 10ms has been assumed. As for the basic case the simulations have been carried out with simultaneous closing in all three phases.

Since two switching events take place in this case namely the connecting of the transformer to the system via a 1000Ω resistor and the shorting of this resistor after 10ms, it is not easily predictable which event causes the higher inrush currents. Hence the analysis can not be restricted to a certain range of the voltage angle but must be extended over a full period of 360°el.

Fig. 7 shows the main results when 1000Ω closing resistors are used. All other parameters are the same as for the basic worst case, i.e. short-circuit power of 30'250MVA, residual flux of 0.68p.u. and polarity +/-/0.

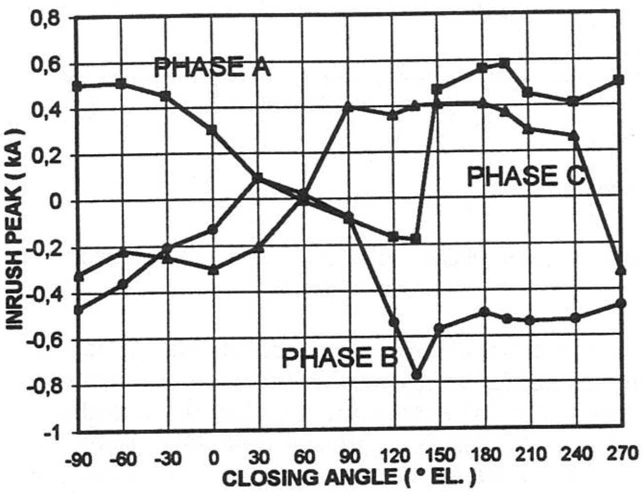

Fig. 7. 1000Ohm closing resistor, inrush peaks as a function of closing angle

The highest inrush current peak with closing resistors amounts to 0.8kA. An optimization of the closing resistor value should be carried out if the closing resistor option is economically and technically acceptable.

Even for the most unfavourable case voltage depression of 1% and total harmonic distortion of 3.1% do not pose any problems.

3. Synchronized closing

Since the residual flux in the different phase windings before closing is not known the only feasible strategy for synchronized closing is to close at the peak value of the line-to-ground voltage. At opposite polarity of residual flux and voltage this will lead to a partial reduction of the residual flux until voltage zero. At the same polarity of residual flux and voltage a limited flux only is added to the existing residual flux. The expected maximum inrush current peak should then lie in between the worst basic case and the worst case without residual flux.

It is known from previous investigations that synchronized simultaneous closing in all three phases according to this strategy would result in a reduced inrush current in the reference phase (voltage peak), but would still yield high inrush currents in the other two phases. Hence the proposed procedure is to close the first phase at voltage peak and the other two phases ¼ period later [6]. This does not correspond exactly to the voltage maximum in these phases but to a voltage which is close to the peak.

Here also the polarity combinations of the residual flux +/-/0 and +/0/- have to be checked for closing at the positive voltage peak value as well as for closing at the negative voltage peak value.

Finally mechanical tolerances cannot be avoided even if modern circuit-breakers have short closing times and consequently a high degree of constancy in operating times. For the simulations deviations of ±1ms from the ideal synchronizing instant (voltage peak) have been taken into consideration. The results are given in Fig. 8a and b.

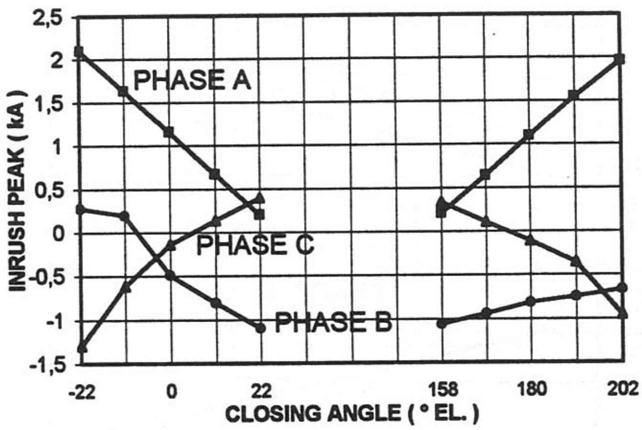

Fig. 8a. Synchronized closing, residual flux +/-/0

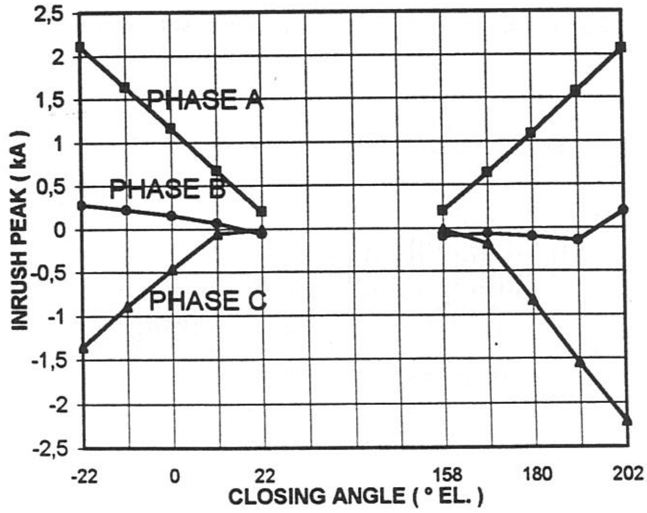

Fig. 8b. Synchronized closing, residual flux +/0/-

As to be expected the highest inrush currents occur at the maximum deviation of ±1ms from the ideal instant. The maximum inrush current of 2.21kA is considerably lower than the worst case current of 3.59kA. Closing at the ideal instant would result in inrush current maxima of only 1.2kA. The currents at the opposite side of the unfavourable tolerance band are very modest too.

Voltage depression and THD reach 3.3% and 5.8% respectively in the worst case with synchronized closing.

4. Closing without residual flux

The worst case for this condition is closing at any voltage zero crossing and has been already treated in paragraph IV.1(see Fig. 4). The maximum inrush current amounts to 1.84kA.

The main question is how the condition residual flux ≈ zero could be reliably achieved. Neglecting opening operations of the generator and transformer circuit-breaker (h.v.-side) caused by protection relays, the procedure to take a generator out of operation could be to discharge the generator, to open the h.v. side circuit-breaker of the step-up transformer, to regulate the generator voltage close to zero and to open the generator circuit-breaker. Such a procedure would avoid any significant residual flux in the step-up transformer.

Some operations caused by protection relays which lead first to the opening of the h.v. transformer circuit-breaker, could also lead to zero residual flux by regulating the generator voltage down to zero. In case of a protection relay activated opening of the generator circuit-breaker however the step-up transformer remains in a state of residual flux when finally the h.v. side circuit-breaker opens.

5. Synchronized closing without residual flux

Obviously this measure represents the ideal case. The same strategy as described in paragraph IV.3 is used here too, i.e. closing at voltage peak in one phase and closing ¼ period later in the other two phases. Again a deviation from the ideal instant due to mechanical tolerances has to be expected, which is allowed to be larger now.

Fig. 9 shows the results for a range of ±1.5ms deviation from the ideal closing instant.

The maximum inrush current peaks of about 1.2kA occur at both deviation limits; at the ideal closing instant there is no inrush at all.

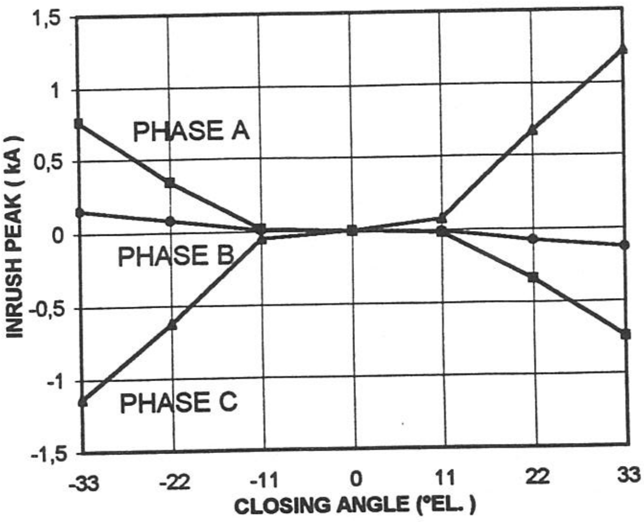

Fig. 9. Synchronized closing without residual flux

V. CONCLUSIONS

The inrush currents of the largest step-up transformers in Guri Hydro-Power Plant have been simulated in case of energization from the h.v. side and for worst case assumptions i.e. most unfavourable closing instants and residual flux.

- The worst case maximum inrush peak at the 765kV side is 3.6kA. This value is low compared with the maximum asymmetric short-circuit peak current of the transformer (3-phase short-circuit at the l.v. side) of 9.6kA. On the other hand it leads to a substantial voltage depression and total harmonic distortion of the 765kV bus voltage especially if a reduced short-circuit power of the system is effective.
- The time constant for the decay of the inrush currents is in the range of 0.8sec.
- Means to reduce the inrush currents are closing resistors, synchronized closing, prevention of residual flux and combinations of these measures.
- For practical reasons the same closing resistors as used for the line circuit-breakers i.e. 1000Ω have been assumed for transformer energization. The maximum inrush current peak is reduced to 0.8kA this way. By optimizing the value of the closing resistor even lower inrush currents might be achieved.
- Synchronized closing requires closing at the instant of the peak value of the 765kV line-to-ground voltage in the first phase and delayed closing (1/4 period later) in the other 2 phases. Provided that a tolerance of ±1ms regarding the ideal closing instant can be maintained, the maximum inrush current peak amounts to 2.2kA.
- Prevention of the residual flux would result in maximum inrush current peaks of 1.8kA. Residual flux could be prevented at operational opening manoeuvres by regulating the voltage of the generator connected to the transformer down to zero. In case of protection relay activated opening of the generator circuit-breaker residual flux cannot be avoided. Since such an event cannot be excluded this measure would in some cases lead to substantial inrush currents.
- Combination of synchronized closing and prevention of the residual flux leads to extremely small inrush currents. This combination allows to extend the tolerance limits regarding the ideal closing instant to ±1.5ms. For these conditions the maximum inrush current peaks amount to 1.2kA. But again this

strategy is not consistent in case of protection relay activated opening of the generator circuit-breaker. Hence synchronized closing is considered to be the most efficient and most economical measure for the reduction of the step-up transformer inrush currents in Guri Hydro-Power Plant, this way favouring the use of generator circuit-breakers (between generator and step-up transformer) granting enhanced plant availability and flexibility of operation.[7]

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