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Effective Management of Transformer Inrush during Restoration of a Typical Industrial Power System

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ABSTRACT: Very often it is noticed that complete black out takes place in an industrial plant for occurrence of an abnormal condition in the power distribution system. Generally restoration of power is done through available Emergency Diesel Generator (EDG) sets in the plant to ensure power supply to the critical loads. It is observed that during initial load pick up phase switching inrush of the distribution transformers creates enormous difficulty in synchronisation of EDG sets resulting in secondary collapse which may again delay the entire process of emergency power restoration. This delay may create irreversible damage to the power sensitive critical loads. Similar such situation was faced in a large chemical plant and was studied further to overcome the situation through cost effective measures. In these paper mitigation measures of magnetizing inrush current due to switching of downstream distribution transformers at 6.6 KV level has been devised to avoid synchronisation failure of large EDG sets during emergency power restoration.

KEYWORDS: Mitigation of Effect of Magnetizing Inrush, Emergency Diesel Generator (EDG), Safe Emergency Power Restoration.

I.INTRODUCTION

Switching of transformers is considered as a critical event in the operation of an Industrial power system. When a transformer is energized, due to momentary saturation of transformer core during magnetising process, it generates very high value of transient current known as inrush current. This inrush current has tremendous stress on system equipment, protection co-ordination and synchronisation etc. The voltage dip in the bus reaches beyond acceptable limit due to high surge current, sometimes 9/10 times the full load current and the same may de-synchronize EDG sets just connected with the system for emergency power restoration. Due to involvement of switching of several load transformers in large power distribution, successful synchronisation and load pick up of EDG units during black out condition is really a challenging task. This system criticality is generated due to the aforesaid unpredictable system transients followed by energization of transformers. In the subsequent sections we will attempt to focus on phenomenon, reasons, effects and mitigation plans of the effect of inrush current to ensure steady synchronisation of EDG and load pick up through transformer switching. A case study with simulation results have also been incorporated for a large chemical plant where delay in restoration of power supply for some critical loads may create irreversible damage and jeopardize the production process.

II.MAGNETIZING INRUSH - CAUSE & EFFECT

Transformer Inrush is generated due to the nonlinear relationship of flux and magnetizing current as transformer core enters into saturation mode. It is not only the high magnitude of inrush current but its composition (high DC component and harmonics) and duration also are the causes of concern which severely affects the stability of the system.

This disturbance can be severe enough to carry the transient swing of rotor angle beyond 180° which in turn results in the slipping of poles for the connected generators and create lossof synchronism with the power system.

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Inrush current is found to be a function of several factors like magnitude of remnant flux in transformer core, Nonlinear magnetizing characteristic during saturation, Magnitude of source voltage and impedance, the switching instant and short circuit power of the source including VAR absorption capacity .

The general equation that gives the amplitude of inrush current as a function of time [1] can be expressed as

$$i(t) = \frac{\sqrt{2}Vm}{Ze} * Sw * Ks * (\sin(\omega t - \theta) - e^{\frac{-(t-t0)}{\tau}} * \sin\varphi$$

Where,
Vm – maximum r.m.s voltage across the transformer primary;
Ze – equivalent impedance under inrush;
θ – Angle of energization;
t – Time of enerzization;
t0 – time at core saturation;
τ – Transformer winding time constant during inrush;
φ – Function of t0;
Sw – constants for 3 phase winding connection;
Ks – constants for short-circuit power of network.

III.CASE STUDY

A case study of loss of synchronism for the plant EDGs as encountered during switching of transformers in a reputed large chemical plant in India have been carried out and is described below.
The subject plant is a renowned producer of Purified Terephthalic Acid (PTA). The plant has been categorized into three (3) different processes, namely HP Plant, DP plant and CHH Plant.
The plant is getting main power supply from the state utility at 132kV level. Afterward, it is stepped down to 6.6kV via two (2) nos 35MVA transformer. There are three different 6.6kV switchgears for HP Plant, DP plant and CHH Plant. HP plant is connected with DP and CHH plant at 6.6kV via tie lines. During normal operation one transformer is connected at HP plant and another is connected with DP pant. CHH plant is connected with HP plant through the tie cable of 6.6kV. The tie between HP and DP plant remains open in normal condition.

The power distribution philosophy for all the three plant is described as below:
6.6/0.433kV transformers of different sizes have been found for downstream distribution. Motor feeders above 150kW are fed from 6.6kV Board while rest are fed from 415V Board. Total plant load comes to the tune of 45MW out of which critical survival load is around 5.5 MW.
A block diagram for the power system of the chemical plant up to 6.6 KV level has been shown below in the Fig 1.

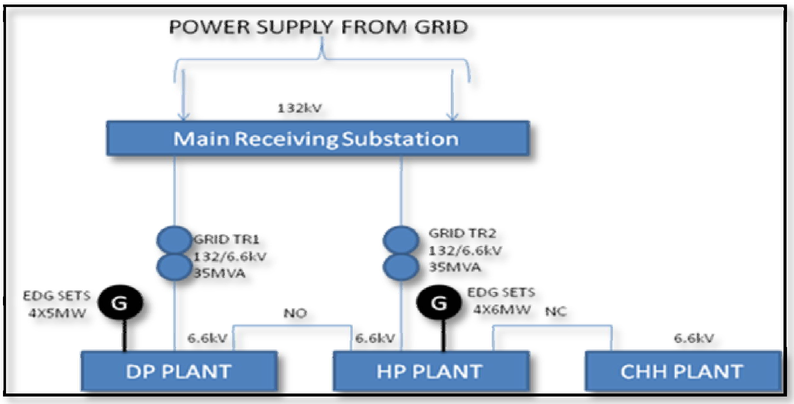

Fig. 1: Block Single Line Diagram of the Power Distribution of the Plant

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It is observed recently that due to grid disturbances 132kV grid power failed and became isolated resulting complete black out and tripping of the process plantloads. For resuming the process, critical loads were to be restored within 60 sec as per the requirement of the plant.

The plant is having 2x 6 MW EDG sets at HP plant to run the critical loads to cope up with such situation.

On occurrence of complete black out / islanding from grid, the HP plant DG sets needed to be synchronised one after another and the critical load buses were energized. It was found that the load side 6.6/0.433kV distribution transformers were switched on almost simultaneously for quick restoration of critical loads.
There is total twenty four (24) nos. distribution transformer in the range of 0.8MVA to 2 MVA, 6.6/0.433kV which are fed from the DG supply during emergency condition.
It was found that the DG sets went out of step and failed to pick up the loads upon switching on the distribution transformers.
While analysing the root cause of the failure, the study team collected all the data and gathered the sequence of operation followed for switching all the emergency loads.
Based upon the data collected the critical power system was modelled in PSCAD and represented as shown in the Fig. 2 below.

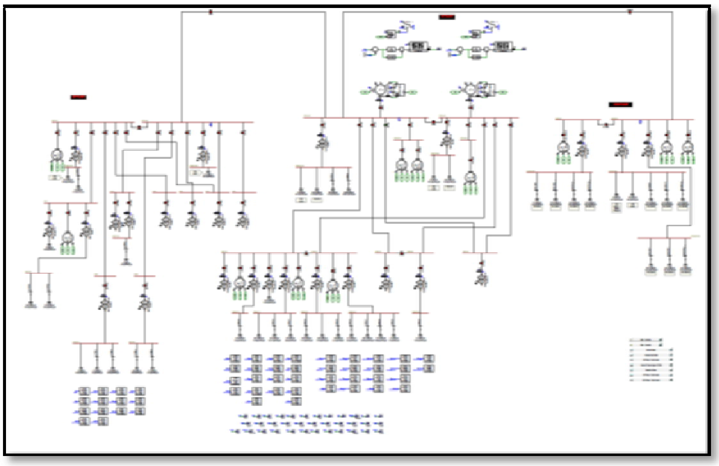

Fig. 2: Emergency Power System of the subject plant

The simulation results of the transformer magnetizing inrush current for the operating sequence followed has been shown in Fig. 3 below. The highest amplitude of magnetizing inrush current of a 2 MVA, 6.6/0.433kV transformer appears to be 1.7kA at 6.6kV side which is almost 10 times of the full load current.

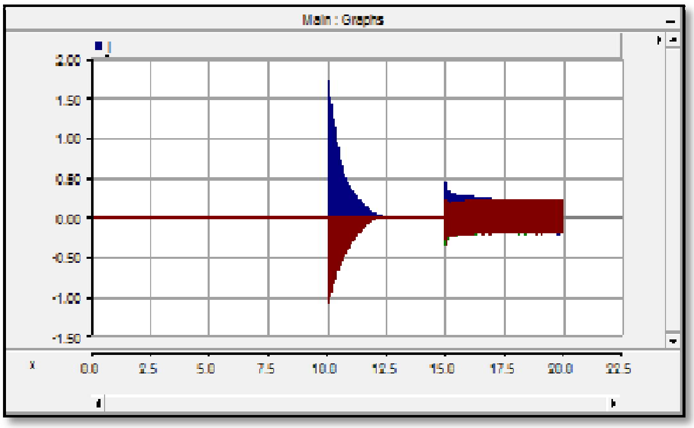

Fig 3: Simulation result of magnetizing inrush current (typical) of 2MVA, 6.6/0.433kV Transformer

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The simulation result of frequency analysis of the inrush current has been shown in Fig 4 below. It is found that after fundamental, 2nd harmonics is predominant which matches with the typical nature of the inrush current.

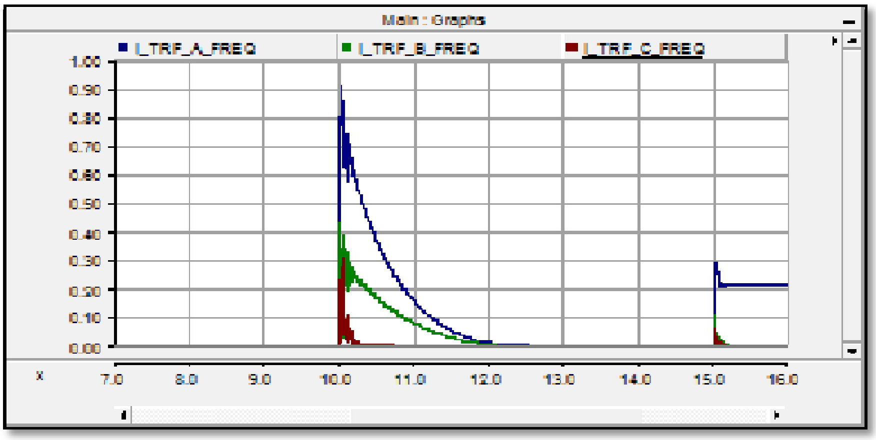

Fig 4: Simulation result of 'R' phase frequency component (typical) of 2MVA, 6.6/0.433kV Transformer, (fundamental – top, 2nd harmonic – middle, 3rd harmonic – bottom)

The simulation result of voltage profile of 6.6 bus after connecting the EDG is shown in Fig. 5 below. It is found that severe bus voltage collapse due to voltage drop for magnetizing inrush effect of the transformers.

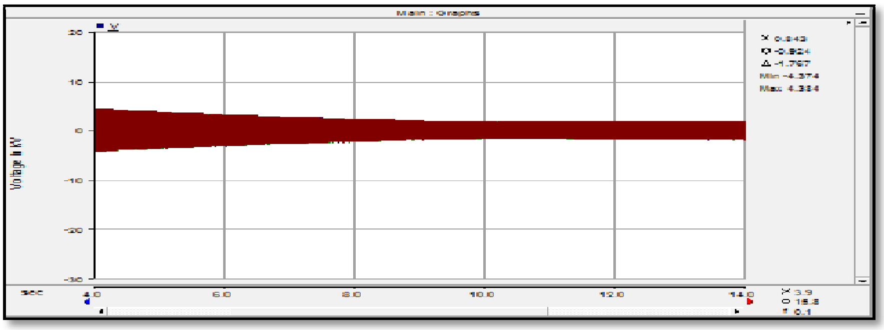

Fig 5: Simulation result of voltage profile of EDG bus (6.6kV)

The simulation result of rotor angle of the EDG sets has been shown in Fig 6 below. It is found from the result that DGs are going out of step with rotor angle variation more than 3c.

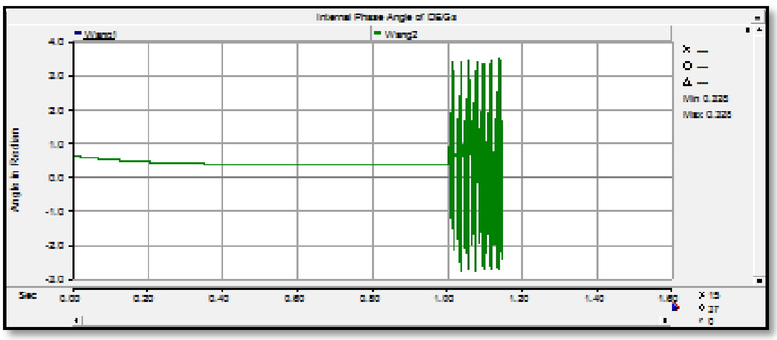

Fig 6: Simulation result of Rotor Angle output of EDGs

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IV.MITIGATION PLAN

The phenomenon of transformer inrush is dynamic in nature and largely depends on system configuration. There are ways to mitigate the magnetizing effect but they are more system specific than a generalized solution. Some of the mitigation methods are as follows [2]

- Pre Insertion Resister in circuit breaker
- Low Impedance Charging
- Load the transformer to its minimum possible load prior to proceeding with energization

With the above mitigation plan, new components are required to be introduced which has cost and time involvement.

So the solution has been thought of in a different way without involving any additional investment for any new equipment or parts.
Change of operating sequence has been thought of and studied with simulationmodel with different possible sequences. It is observed that the final suggested pattern of switching sequence works out successfully to reduce the inrush causing out of step of EDGs. The operating sequence is described below:

First one 6 MW DG is started and the loads in HP and DP plants are switched on sequentially as per the Table - 1 described below.

TIME in Secs	DP PLANT	HP PLANT	CHH PLANT
	BLACK OUT		
0		EDG AUTO START	
		1st EDG CONNECT with HP BUS	
30		EDG AUX. START 2TR-01 , 2TR-02 , 2TR-13	CHH TIE FEEDER BETN DP-HP ON 5TR-02
31	TIE FEEDER BETN DP-HP ON TR-01 , TR-02 , TR-13 , TR-41		
32		2TR-12 , 2TR-31	
34	TR-11 , TR-21 , TR-31		
36		2TR-11 , 2TR-21 , 2TR-22	
38	TR-12 , TR-22		
45	CW PUMP START (HT MOTOR)		CW PUMP START
47	TR-32	2TR-32	5TR-03
49	TR-51	2TR-41	5TR-01
55		CW PUMP START (HT MOTOR)	
60	IA/ PA COMP. START (HT MOTOR)		
70		IA/ PA COMP. START (HT MOTOR)	
80			HP CHH HO CIRCULATION PUMPS
90			DP CHH HO CIRCULATION PUMP
100	DP Priority Group-4		
110		HP Priority Group-5	
120			CHH IA/ PA COMP. START
135		2nd EDG CONNECT with HP BUS	
155	DP Priority Group-5		CHH-A ID FAN
165	DP Priority Group-6		CHH-B ID FAN
170	AG-1731 : TR Charge		
175			CHH-C ID FAN
185		HP Priority Group-6	CHH-A FD FAN-1
195		HP Priority Group-7	CHH-A FD FAN-2
205		HP Priority Group-8	CHH-B FD FAN-1
215		HP Priority Group-9	CHH-B FD FAN-2
220		2AG-1311 : TR Charge	
225			CHH-C FD FAN-1
235			CHH-C FD FAN-2

Table 1: Suggested sequence of operation for restoration of critical loads

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The effectiveness of the proposed technique is checked by the simulation results which are produced below. The simulation result of active power output w.r.t. time of the EDGs as per above starting sequence is shown in Fig. 7 below. It is found that the active power output is matching with the load demand as envisaged in the Table 1 above.

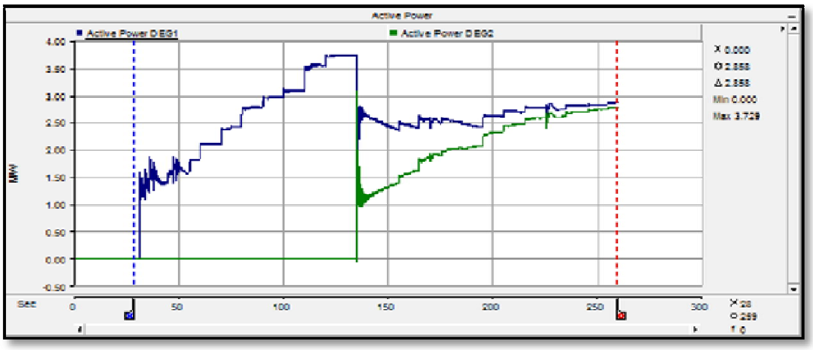

Fig 7: Simulation result of active power outputs of EDGs

The simulation result of reactive power output w.r.t. time of the EDGs as per above starting sequence is shown in Fig. 8 below. It is found that the reactive power output range of the EDGs are well within their capability curve.

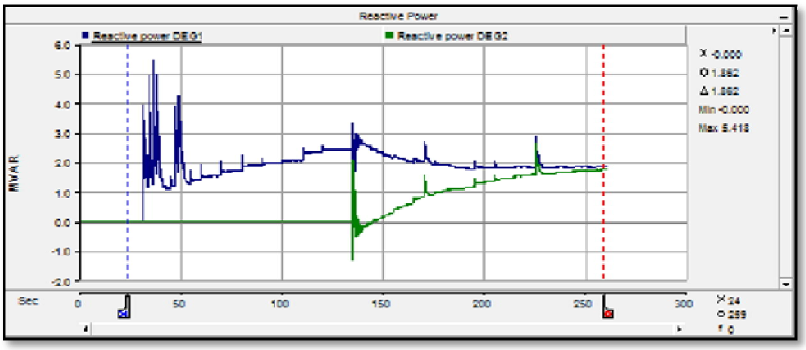

Fig 8: Simulation result of reactive power outputs of EDGs

The simulation result of voltage profile of 6.6 bus w.r.t. time after connecting the EDGs as per the starting sequence envisaged in Table-1 above is shown in Fig. 9 below. It is found that the reactive power output range of the EDGs are well within their capability curve. It is found that voltage dip in load bus due to transformer inrush is within 20% in the first cycle and 3-5% thereafter.

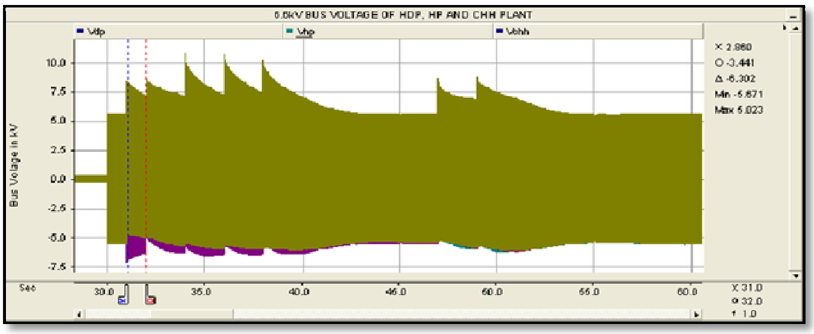

Fig 9: Simulation result of voltage profile of EDG bus (6.6kV)

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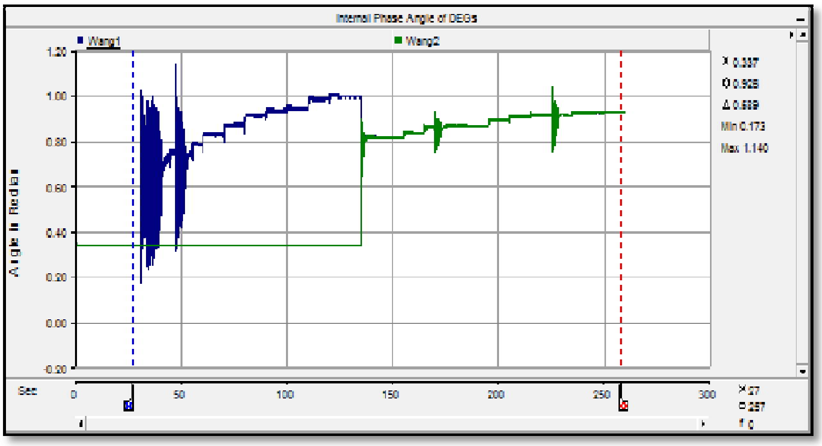

Fig 10: Simulation result of Rotor Angle output of EDGs

It is found that the maximum internal phase angle (Fig 10) has reduced to 1.14^c and after synchronization of 2nd EDG the same has reduced to less than 1^c.

V.RECOMMENDATIONS

Due to change of switching sequence it has been observed that the rotor angle swing during magnetising inrush is coming within the acceptable limit thereby reducing the threat for going out of step. The situation improves after synchronisation of the 2nd EDG and load pick up becomes smooth. Active and reactive power outputs (Fig 7 & 8) from both the machines are also found well within the EDG capability curve.

Voltages at 6.6kV buses are found within ± 10% during switching operation of Transformers, HT motors (Fig -9).

As per IEEE 399 stipulation, the transient overshoot of the rotor angle should never exceed 2c or if the root cause of rotor swing is quickly removed, the machine may continue with the system in synchronised condition. The rotor angle then oscillates with gradually decreasing swings until it settles to its final steady value (less than 90°). The oscillations are damped by electrical load and mechanical & electrical losses in the machine and system, especially through the damper windings of the machine.

The result of internal phase angle depicts that the transient overshoot of the rotor angle never exceeds 2^c and finally settles at around 0.8^c.

Hence, the suggested operation philosophy for restoration of critical loads of the plant after black out satisfy the requirement of controlling the effect of magnetising inrush without additional cost involvement and without violating the condition for process requirement.

The same sequence has also been vetted by the process people for implementation.

VI.CONCLUSION

In this paper a cost effective method for controlling the effect of overall magnetising inrush current due to switching of load transformers during start up time of EDG sets has been proposed. The proposed scheme aims to prevent the EDG sets going out of step and failing in emergency load pick up by changing only the switching sequence. This strategy on the basis of the reducing peak load is quite different from other standard approaches of inrush current reduction. This control strategy is easy to implement because the operating sequence is effective in reducing the overall start-up inrush current. This is achieved without any additional hardware and without the need for a separate source. The same philosophy may be followed for any such industrial plant facing the similar problem provided that the simulated switching strategy fulfils the process requirement.

VII.ACKNOWLEDGEMENT

Both the authors were employee in Tata Consulting Engineers Ltd(TCE) , Kolkata and they carried out the studies as a part of TCE team on the power systems of the chemical plant situated at Eastern India. The study is the basis of formulating this technical paper. We thankfully acknowledge the contribution of the technical team of the client MCPI, Haldia while completing the study successfully.

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