Simulation of Transients in Very Large Scale Distribution Networks by Combining Netlist and Graphical User Interface

I. Kocar, J. Mahseredjian, R. E. Uosef, and B. Cetindag

***Abstract*—A large scale distribution network with secondary grid network details can easily have ten thousands of nodes and become very complex to study using an Electromagnetic Transients Type (EMT-type) tool. This paper promotes a mixed design tool that connects "visually built" parts with the rest of the network maintained with text files or so called Netlist. This approach allows quickly modeling the distribution network with full details in a transient simulation environment while improving the simulation experience in many ways. Having full circuit details allows the initialization of transient analysis with correct multiphase load flow solution. Once the full circuit simulations are available it is possible to tune equivalent circuits and evaluate the order of approximation errors. A real North American urban distribution network is studied as an example in this paper. Both steady state and transient analysis are performed. Capacitor switching at the substation level is the transient phenomenon studied. A discussion on available guides and technical documents related to switching of shunt capacitors is provided in conjunction with the simulation results.**

***Index Terms*—Electromagnetic Transient Analysis, Distribution Systems, Capacitor Switching, Simulation Tools, Graphic User Interface**

I. Introduction

There is a surge of interest in dynamic analysis of distribution networks using EMT-type programs mostly because of the interest in connecting distributed generation to distribution systems [1]-[7]. The size of the systems studied remains relatively small.

Although the resulting number of control and electrical circuit components is huge, it has been demonstrated that it is possible to build and analyze large scale distribution and transmission networks in EMT-type programs [8]-[11]. The large scale distribution networks in EMT-type programs are maintained with text files due to the structure of GUI design and capabilities different than steady state planning tools that are allowing automatic circuit layout.

The distribution systems have traditionally been studied with steady-state tools such as power flow programs and short circuit packages. Distribution system databases that are readily available contain sufficient information to be studied in steady state tools: list of components, specifications, ratings and connectivity information. It is possible to develop translators to convert input data from power flow programs such as Poly Voltage Load Flow (PVL) program, a proprietary software developed by Con Edison [12], into EMTP-RV [13] design file called Netlist [11]. Component model details missing in the source data but necessary for accurate time domain simulation of transient conditions can be embedded into the design file in various ways. These details include, among others, nonlinear magnetization curve of transformers, relay settings and network protector controls. However, for certain transient studies such as capacitor switching at the substation, some crucial details will be still missing such as the impedances of busbars, lengths of relatively short busbars or cables/busbars connecting cap banks to synchronous buses. These details, having no significant impact on the steady state solution, are simply ignored in power flow programs and cannot be always found in databases either. They need to be maintained by examining the blue prints or even by site visits. As a conclusion, it may become necessary to reconstruct some parts of the design manually and add new components.

This paper presents a mixed design approach. The substation details are modeled using the Graphical User Interface (GUI) while the feeders and related details are maintained with text files (Netlist) with several subcircuit layers of which the data is extracted from the PVL database. Since the previous version of EMTP-RV (2.4) did not allow electrically connecting the GUI with such multilayer text files, a patch for macro files is written. This modeling approach provides flexibility since it is possible to study several transient scenarios associated with substations by just using the mouse-based functions of the GUI.

Following the assembly of a detailed design file, various transient phenomena including capacitor switching in the substation can be studied. As stated in [14], when a capacitor bank is energized or de-energized, current and voltage transients are produced that affect both the capacitor bank and the connected system [14]-[16].

The contributions of this paper can be listed as follows:

- Promulgation of hybrid designs that integrate Netlist maintained circuit layers with GUI maintained circuit layers for the transient analysis of large scale distribution systems;
- Assessment of errors committed due to equivalent circuit

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approximations in capacitor switching studies for a large scale urban distribution network with secondary grid networks;

- Discussion of IEEE guides and published technical documents in the light of simulations performed with full circuit details.

II. Network Modeling

In this section the network case under study and the modeling approach are described.

As mentioned in the introduction the distribution network is built with a hybrid modeling approach.

Fig. 1 presents a partial snapshot of the main layer of the design where the substation bus details and switches can be visually seen. The block on the left side is a subcircuit with electrical pins that redirects to external Netlist (text file) containing details of the distribution network, i.e., primary network feeders, secondary grid and spot networks, and associated devices. The simplified topology of such a network is presented in Fig. 2. Although there are two voltage levels at the secondary, i.e., 460 and 208 V, only the 208 V grid is shown in the figure.

Since the capacitors are connected to the substation, this modeling approach allows studying several capacitor switching scenarios efficiently by just manually manipulating the substation circuit using the GUI.

All the devices in the network are modeled in detail considering the requirements for different transient studies such as capacitor switching, short circuit and DG integration studies.

The network data summary is provided in Table I and it reveals that the network size is prohibitively large to be entirely reproduced as a visual circuit using the GUI manually or without a sophisticated automated drawing tool.

The circuit breaker controls are built using standard control devices. The network transformers are modeled with saturation details. The network protectors associated with network transformers are modeled with full control options and settings. The short cable sections are modeled with constant parameter PI models with capacitance distributed to ends. In overvoltage studies, the Wideband Model (WB), which is the implementation of Universal Line Model in EMTP-RV, is used for the relatively long feeder under observation. Note that the distribution of power in this network is done by using cables only which makes the system particularly interesting for capacitor switching transient studies due to the interaction between capacitor banks and distributed cable capacitance. There are 28 primary feeders in the network which result in high cable capacitance that cannot be neglected. The loads are modeled with PQ constraints. The substation transformers are modeled with leakage impedance data and generic saturation details. Tap positions are adjusted in order to obtain 1 pu of voltage on the secondary bus in the load flow solution.

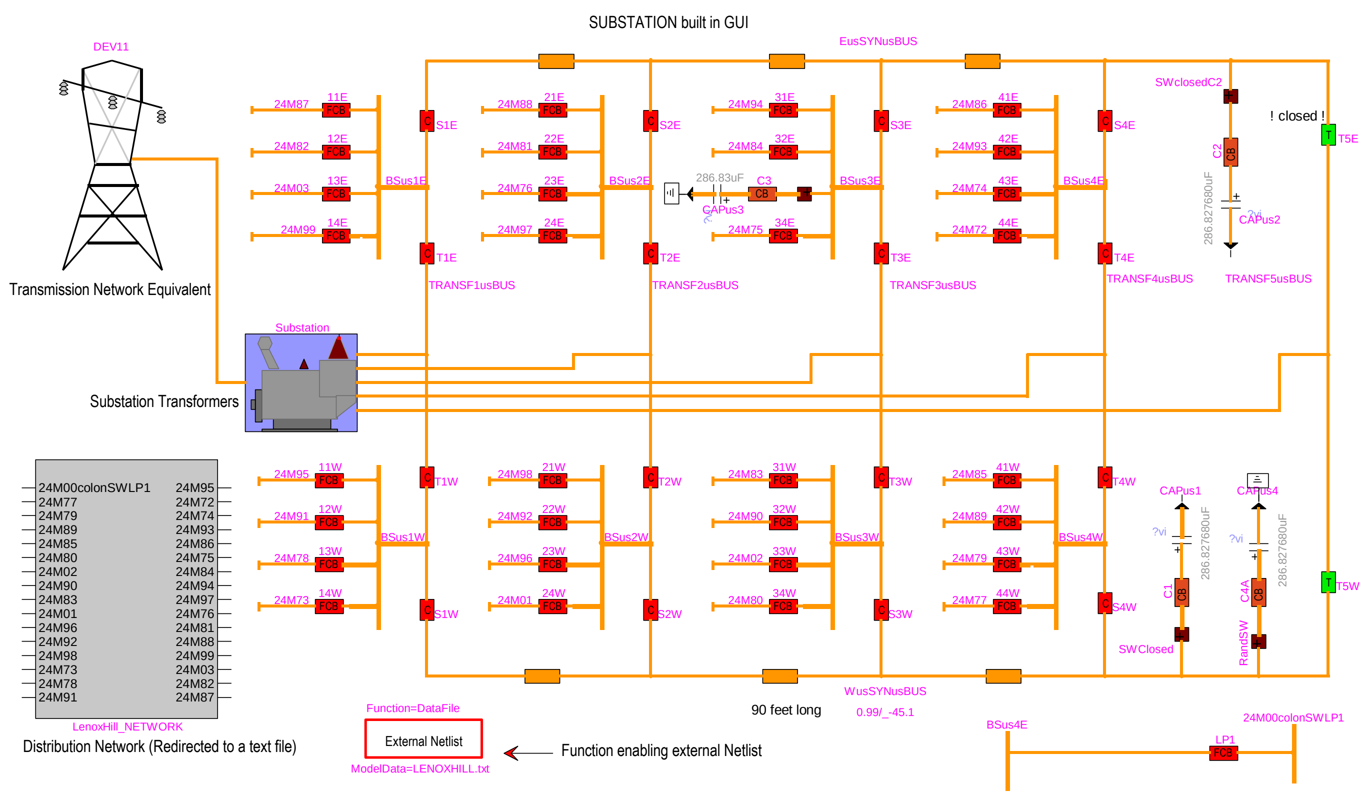

Fig. 1 Substation design: circuit breakers, feeder starts, capacitor banks and busbars

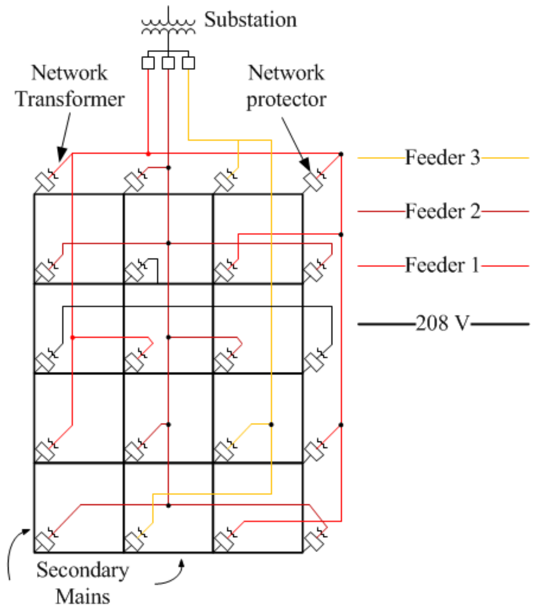

Fig. 2 Simplified topology of a grid network

TABLE I
SUMMARY OF DEVICES*

Summary on network devices		
Name	Number	Number of phases
Source V with Impedance	1	3
Network Transformers	424	
Substation Transformers	5	
RLC branches	2735	
Cable/line sections	6175	18525
Ideal switch	1692	
Controlled switch	204	
Nonlinear inductance	1311	
PQ Load	4443	
Control-system signals	10434	

*Total number of network nodes including internal nodes is 17234. The size of the main system of equations is 20513.

Among other equipment, the substation is equipped with five 100 MVA transformers, three 20 Mvars capacitor bank units with ungrounded wye connection and two emergency gas turbines coupled to synchronous machines each having a capacity of 20 MW with 0.85 lagging power factor capability. It is proposed to add another 20 Mvars capacitor bank to the substation in order to support the system voltage and reduce reactive power flow. A maximum of four transformers or three transformers with two gas turbines are allowed to be in service at a given time.

The impedance per foot of busbars is taken as follows (the frequency dependence is ignored)

$$X = 41.67\,\mu\Omega/\ foot$$
$$R = 0.0119244\,\mu\Omega/\ foot \quad (1)$$

The capacitor banks are connected through 100 to 200 feet 1000 kcmil copper cables. The impedance of cables constitute the primary source of limiting impedance for back-to-back capacitor switching transients as it is significantly greater compared to busbar impedances.

The subcircuit embodying the substation transformers and gas turbines is shown in Fig. 3. It is assumed that the peak load in summer is 304 MW with 0.90 pf. The 60 Hz impedance of each transformer is $0.015 + j0.75\Omega$. The voltage rating is 138 to 13.8 kV with 12% tap changing mechanism on the secondary.

The transmission network is modeled with its Thevenin equivalent for load flow solution.

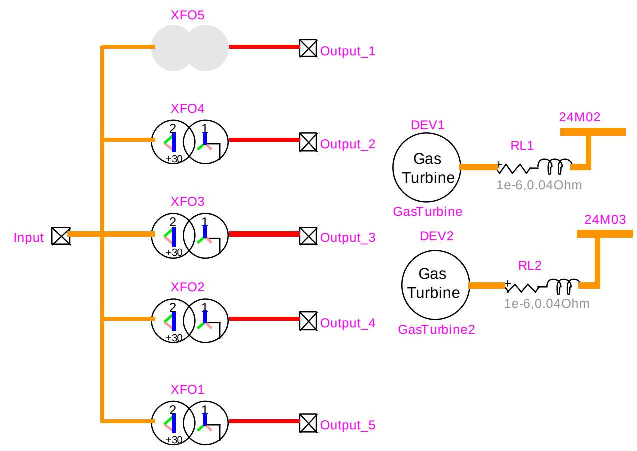

Fig. 3 Substation transformers

III. LOAD FLOW AND TRANSIENT SOLUTION

The CPU Timers for the multiphase load flow solution are presented in Table II. The solution is performed by using a Lenovo T520 laptop (with i7-2640 CPU 2.80 GHz, 8 GB RAM). The load flow algorithm is based on modified-augmented-nodal analysis (MANA). It is shown that MANA provides a generic multiphase load-flow formulation method capable of handling arbitrary network topologies and can be easily expanded to accommodate various component models [17]. It also avoids many theoretical complications by providing a systematic method for deriving the Jacobian matrix term. Although sparse matrix techniques are used for both the LU factorization and update of the Jacobian matrix, the optimizations regarding ordering and symbolic ordering discussed in [17] are not applied. Note that, most of the solution time is due to iterative updating of the Jacobian matrix.

The total CPU Time for a transient simulation of 80 ms with 5 microseconds of time step is 971 seconds. In this simulation a capacitor bank is energized. Given the number of control devices and electrical nodes, this time is not considered here to be prohibitive for an offline simulation to perform studies with full circuit details. If the network protectors are modeled with ideal switches the simulation time reduces to 97 seconds.

TABLE II
CPU TIMERS LOAD FLOW

CPU timers (s)	
Prepare data	2.29321
Read data	.03120
Device initialization	3.43202
Steady-state solution (load flow iterations)	39.06265
Number of iterations	3
Total	44.83469

IV. CAPACITOR SWITCHING TRANSIENTS

A. Capacitors in Distribution Systems

Fig. 4 presents the application of shunt capacitor banks in power systems [18].

As the power systems become heavily loaded, shunt capacitor banks are indispensable for reliable operation. In distribution systems, three types of shunt capacitor banks are typically deployed:

- Large capacitor banks at the substation;
- Distribution capacitor banks along the feeders, especially along long aerial lines;
- Power factor correction banks at the secondary level.

In this study, the network is urban with heavily meshed secondary network topology, therefore no distribution capacitor banks are considered and the study is focused on the switching of substation capacitor banks.

B. Switching Transients

When a capacitor bank is energized or de-energized, current and voltage transients are produced that stress both the capacitor bank and the connected system [16]. When energized, a capacitor acts like a short circuit initially and draws a high frequency, high magnitude inrush current until its voltage stabilizes and gets synchronized with the system voltage. If the capacitor has trapped charge it will have an impact on the transients as well; the worst case happens when the capacitor has the inverse voltage of the system voltage at the instant of energization. In order to avoid switching on a capacitor bank with trapped charge, a five minute delay is typically applied before reenergizing a capacitor bank. The capacitor units are equipped with large shunt resistances such that the capacitor can discharge to a safe level in about five minutes. Note that a capacitor bank is composed of several capacitor units.

C. Theoretical Aspects

The basic theoretical aspects of transients due to energization of a capacitor bank can be understood using a simplified circuit as given in Fig. 5.

The basic circuit equation is

$$\frac{d^2 v_c(t)}{dt} + \frac{v_c(t)}{LC} = V_s \quad (2)$$

The solution of capacitor voltage is

$$v_c(t) = V_s - \left[V_s - v_c(0)\right]\cos\omega_0 t \quad (3)$$

with $v_c(0)$ being the trapped charge, V_s the source voltage and ω_0 the switching frequency

$$\omega_0 = 1/\sqrt{LC} \quad (4)$$

The capacitor current will be

$$i(t) = \frac{V_s}{(L/C)^{1/2}} \sin\omega_0 t \quad (5)$$

The maximum peak current approximation in the IEEE Guide on shunt capacitor banks [14] for single bank energization is related to (5) as will be demonstrated next.

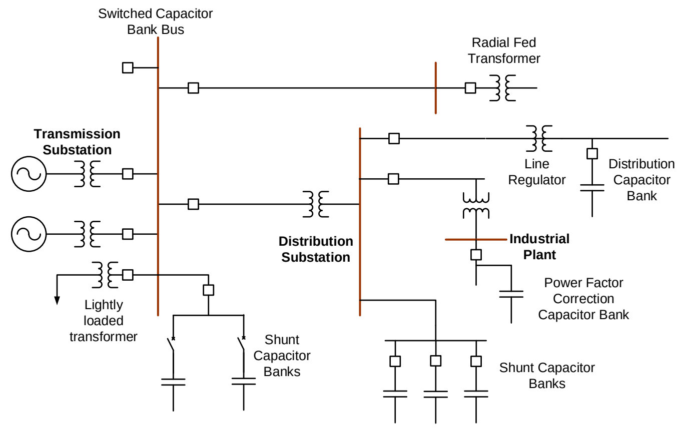

Fig. 4 Capacitors in Power Systems

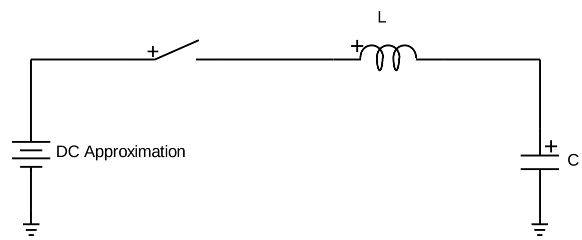

Fig. 5 Simplified circuit to study energization transients

V. TRANSIENT STUDIES

In this section, various capacitor switching studies are performed for the particular distribution network detailed above. The simulated results are compared against the formulations provided in IEEE Standard for shunt capacitor banks, and a discussion on the use of equivalent circuits is provided.

A. Single Bank Energization

In the case of single bank energization, the inrush current is limited by the inductance of the system and the capacitance of the capacitor bank. It is considered that there are no other capacitor banks that are sufficiently close to the capacitor bank that can considerably change the inrush current. The maximum inrush current on a given phase is observed when the capacitor is switched in at the peak voltage point of this phase. Fig. 6 shows the capacitor inrush currents when switched at the peak voltage condition on phase c. Fig. 7 shows the measured RMS current through the switching device with a signal frequency of 60 Hz. In this configuration the number of transformers in service is 4. The rating of the capacitor bank is 20 Mvars. The maximum inrush current is around 15,000 A while the peak RMS current which can be useful for relay settings is 1800 A. According to the IEEE Guide on shunt capacitor banks, the maximum peak current is approximated with the following equation [14]:

$$I_{\max pk} = 1000 \times V_{LL} \times \sqrt{\frac{2}{3}} \times \sqrt{\frac{C_{eq}}{L_{eq}}} \quad (6)$$

where

L_{eq} is the effective inductance of the source (in henries)

C_{eq} is the effective capacitance of the capacitor bank (in farads)

$I_{\max\ pk}$ peak value of inrush current without damping in kA

V_{LL} *line* to line voltage in kilovolts

20 Mvars capacitor bank corresponds to 278.57 μF, the inductance of the source can be approximated as 0.497 mH given that 4 transformers are in parallel. In this case, if the system voltage is taken as 13.8 kV times 1.12 considering the influence of tap positions, the peak value of inrush current will be found as 9.4 kA which is below the simulated value. This significant difference is primarily due to the distributed capacitance of cables present in the network, which cannot be considered in (6).

Note that due to switching in of capacitors the system voltage momentarily drops and rebounds. This will be discussed next.

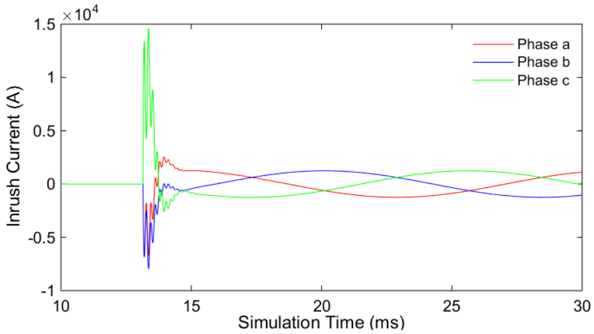

Fig. 6 Maximum inrush current following single bank energization

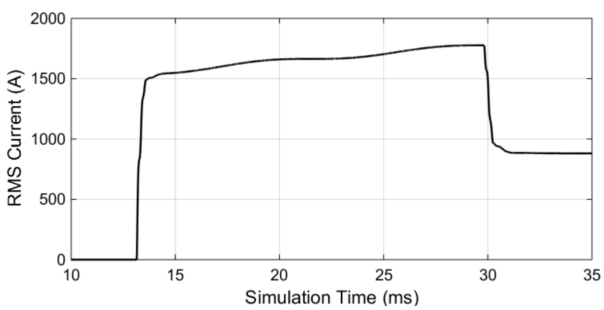

Fig. 7 RMS of maximum inrush current following single bank energization

B. Network Overvoltages due to Single Bank Energization

Single bank energization generates transient overvoltages propagating in the network. In order to have an idea regarding the magnitude and impact of these transients, a feeder with only 6 network transformers is observed. This feeder is schematically shown in Fig. 8.

If all its transformers are out of service, the peak voltage at the end of feeder due to isolated capacitor bank energization reaches up to 1.5 times the nominal peak voltage. In order to correctly evaluate the overvoltages, WB cable models that take into account the frequency dependence of parameters and distributed nature of cables, are used. When standard pi sections with parameters evaluated at 60 Hz are used, the overvoltages propagating in the network are underestimated. Note that the switch on the primary side of the transformer may experience a higher voltage across its terminals due to the polarity difference between the incoming surge and system voltage on the secondary terminals when the network protector is locked and the secondary side of the transformer is connected to the grid network.

If the network transformers are in service, the peak voltage at the end of feeder attains 1.45 times the nominal peak while it is measured as 1.40 times the nominal at the middle of feeder. The transients decay quickly, in less than one cycle, as seen in Fig. 9. This is for maximum damping, i.e., 100% summer loading conditions.

Although it does not seem realistic operational wise, the overvoltage transients for 5% summer loading are also studied, and it is observed that the voltage at the end of feeder reaches almost 2 pu and transients sustain longer, i.e., for several cycles.

In Table III a summary of transient voltages for different locations and loading is presented. Note that time step of EMTP-RV is set to 0.5 microseconds in order to be compatible with the propagation delay of short cable sections. According to the EPRI publication [19], typical overvoltage levels range from 1.2 to 1.8 pu due to switching of substation capacitor banks. This is in agreement with the simulated results in this work.

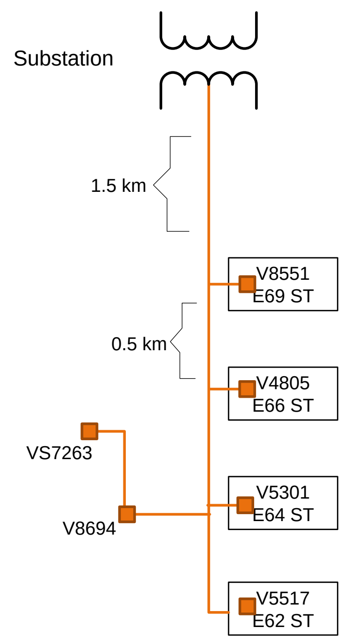

Fig. 8 A feeder with 6 network transformers

TABLE III
SUMMARY OF OVERVOLTAGES

Transformers I/S (4)	**100 % Summer Load**	**%30 Summer Load**
Feeder Location*	Peak Voltage Observed (pu)	Peak Voltage Observed (pu)
Start	1.34	1.38
Middle	1.40	1.60
End	1.45	1.69

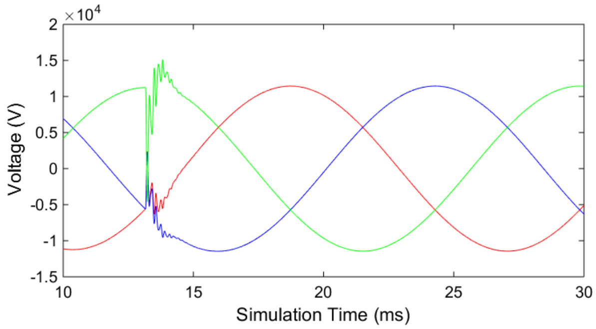

Fig. 9 Overvoltage at the middle of feeder for 100% summer loading

C. Back-to-Back Switching

If a capacitor bank is energized in close proximity to a previously energized capacitor bank, further considerations arise [14]. An inrush current that is much higher than the inrush to an isolated capacitor bank in terms of frequency and magnitude will flow since the limiting inductance is not the system inductance but the inductance between the capacitor banks. The generic equation for this case is given by [14]-[15]:

$$I_{\max\ pk} = 1000 \times V_{LL} \times \sqrt{\frac{2}{3}} \times \sqrt{\frac{C_1 C_2}{(C_1 + C_2) L_m}} \quad (7)$$

where C_1 and C_2 are the capacitor sizes in farads and L_m is the inductance between them in Henries. There are three switched capacitor banks already available in the studied substation each having a capacity of 20 Mvars. With the capacitor bank proposed to be added a total of four capacitor banks are considered here. The simulation of energization of the fourth capacitor bank when the other three are in service produces the maximum inrush current of 35.1 kA as shown in Fig. 10. The peak RMS current is 6.12 kA. Equation (7) on the other hand estimates the worst inrush as 29 kA even if the inductance of busbars is ignored and only the inductance of cables connecting capacitor banks to busbars is considered. This significant difference is due to the omission of damping and distributed capacitance of cables present in the network.

The switching frequencies observed for back-to-back switching cases range in between 2-3 kHz. This is an important parameter since the transient withstanding capability of switching devices designed for capacitor switching should support this transient frequency.

The system overvoltages associated with back-to-back switching is less of a concern compared to the overvoltages due to switching in of an isolated bank because the inrush of the capacitor bank is partially supplied from other capacitor banks in proximity in the form of outrush current. This reduces the voltage dip in the system.

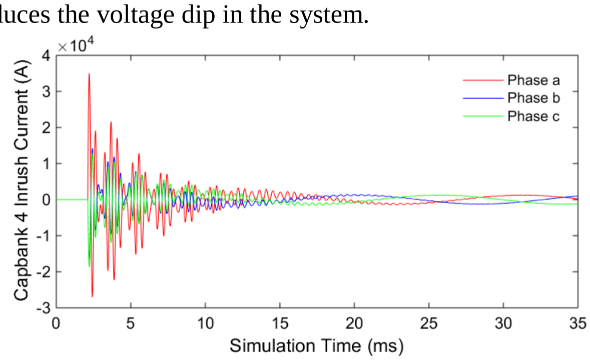

Fig. 10 Max Inrush Current Peak (Switch in 20 Mvars Cap4)

D. Outrush to Short Circuit

The outrush current out of capacitor banks is of concern during short circuit. The capacitor banks will increase the short circuit asymmetrical current duties of breakers by injecting a high frequency outrush current. It should be noted that the short circuit transient current is a function of switching time of the fault and X/R ratio of the network. We are interested in the worst case scenarios.

A typical short circuit current waveform due to a bolted fault on a feeder at the start of the substation is demonstrated in Fig. 11. The maximum peak current is almost 160 kA when there are 4 capacitor banks of 20 Mvars each. The IEEE guide presents the following equation

$$I_{\max\ pk} = \sqrt{\frac{1000}{3f}} \times \sqrt{\frac{Q_c \text{ kvar}}{L}} \quad (8)$$

where L is the inductance per phase between capacitor bank and fault and Q_c is the capacitor bank rating. Again considering only the inductance of cables for L, the maximum peak of the outrush current is found as 171 kA using (8). This value is conservative and close to the simulated result. The circuit breakers of the feeders should be rated for the high frequency and high magnitude outrush current. Limiting reactors can be used for the mitigation of excessive outrush currents. Synchronized switching devices or pre-insertion resistances are effective in reducing the inrush current due to capacitor switching but they do not limit the outrush current in fault conditions.

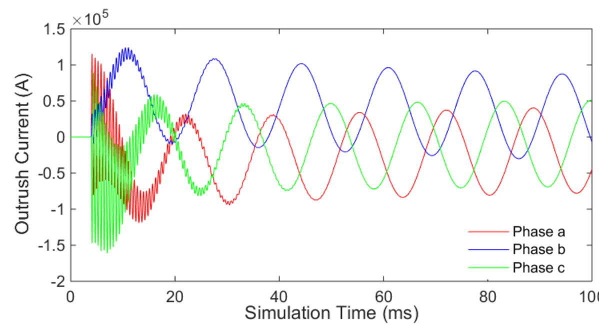

Fig. 11 Typical short circuit currents when capacitors are in service

E. Discussion on equivalent circuits

In order to accelerate the computation time and simplify the modeling efforts, it is possible to recourse to equivalent circuits.

Fig. 12 illustrates an example of an equivalent circuit developed to study single bank energization or back to back switching of the second capacitor bank. The substation transformers, capacitor banks and the impedances between capacitor banks are maintained based on the impedance measurements on the full circuit. Each feeder leaving the substation is represented with either one of the following four equivalent feeders:

- A small cable section terminated with an equivalent load determined by evaluating the share of the feeder from the total load;
- A PI section having the total length of the primary cable feeder, terminated with an equivalent lumped load;
- Several PI sections with distributed load;

- A distributed cable model with constant parameters (CP) terminated with an equivalent lumped load.

Fig. 13 and Fig. 14 show the maximum inrush current on phase c following single capacitor bank energization using equivalent feeders and full circuit. The first equivalent feeder option underestimates the transient inrush current and misses the high frequency component. This is due to the lack of distributed feeder capacitances in the equivalent model. The small cable section in the equivalent circuit does not represent the distributed capacitance of feeders correctly. In the second option, where the distributed capacitance of cables is lumped at the terminals, the peak transient current and the high frequency component of the inrush current are significantly overestimated. The third option with CP model significantly underestimates the transient inrush current and misses the high frequency component. Cascaded PI sections with distributed feeders give similar results with CP model. All these equivalent feeders are used to represent primary feeders but the secondary grid, consisting of kilometers of low voltage cables, transformers and loads, are just represented with lumped loads, which is also a source of imprecision.

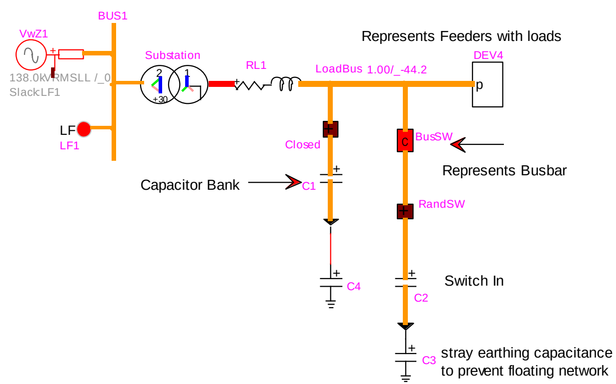

Fig. 12 Equivalent circuit for studying back-to-back switching

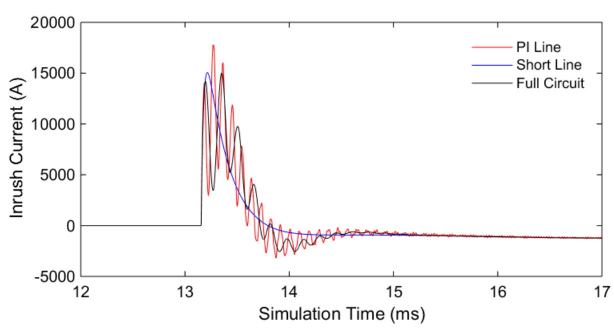

Fig. 13 Max inrush current following single bank energization, with full and equivalent circuits

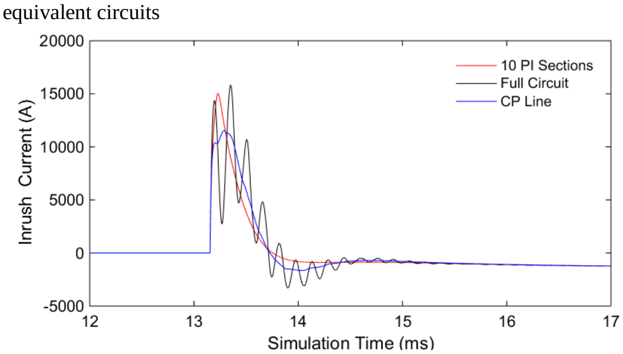

Fig. 14 Max inrush current following single bank energization, with full and equivalent circuits

Fig. 15 shows the maximum inrush current for back-to-back switching of a capacitor bank when one bank is already in service. The equivalent feeder models are successful in estimating the peak inrush current and the high frequency associated with it. This is because the interaction between capacitor banks becomes more important than the interaction between the energized capacitor bank and the network. This time, however, the damping of transients is significantly underestimated.

Fig. 16 shows the maximum short circuit current following a fault on one of the feeders near the substation when there are 4 capacitor banks in service. For this study, the substation configuration given in Fig. 1 is used. The momentary withstanding capability of feeder breakers should be sized by taking into account the outrush currents that come from the capacitor banks. If the short circuit current is evaluated without considering the medium voltage feeders and loads then the peak of the transient short circuit current will be overestimated as seen in Fig. 16. Using equivalent feeders, on the other hand, provides close results this time to those obtained with the full circuit.

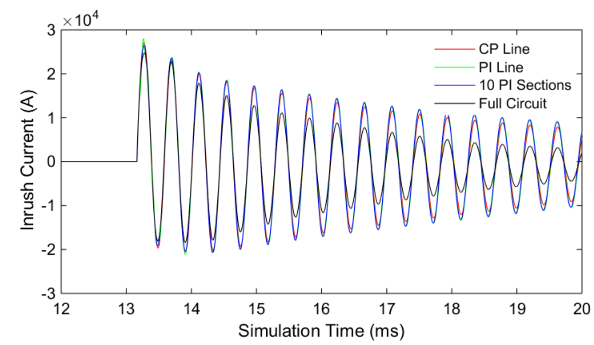

Fig. 15 Max inrush current when one bank is in service, with full and equivalent circuits

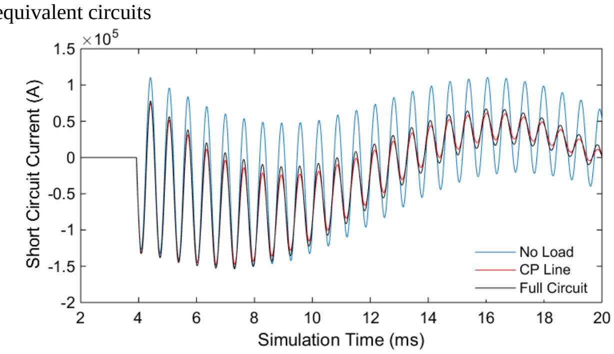

Fig. 16 Short circuit currents on phase c when capacitors are in service

VI. Conclusions

The use of time domain simulations in the analysis of distribution systems is emerging. Typical practice with large scale distribution networks is to maintain them with text files in EMT-type programs. The text files are generated through steady state distribution system tool databases and component wise detailing as required per transient studies. In this paper, a hybrid design tool is promulgated in which a part of the network can be removed from the text file and represented using the GUI. The part of the network built using the functionalities of the GUI is electrically connected to the rest of the circuit maintained with text file. This modeling approach provides significant flexibility for electromagnetic transient studies since it reduces the time from conception to design and allows eliminating the tedious manipulation of text files for different transient scenarios. Moreover, accessing to the electrical nodes of a large network through the GUI gives the potential to access fully to the device library of the hosting tool and to perform various studies such as microgrid integration, DG integration, and interconnection of urban distribution networks.

The need for modeling large scale distribution networks with full circuit details as opposed to equivalent circuits can be best demonstrated by performing comparative studies. For that reason a large scale urban distribution network with secondary grid details is modeled in EMTP-RV using the hybrid design approach promulgated in this paper. The substation of the network and the equivalent subtransmission network are modeled using the GUI since the transient studies are focused on the switching of capacitor banks at the substation. It is demonstrated that not only modeling of a large scale distribution network in an EMT-type program is feasible but it is also possible to verify the trust region of rule of thumb equations and equivalent circuits. It is concluded that the equations in IEEE standard on shunt capacitor banks may be misleading for transient currents due to capacitor switching particularly if the network is composed of several cable feeders and secondary grids. Concerning the equivalent circuits, although the peak transient currents can be estimated in most cases, it is not possible to reproduce the transient current waveforms exactly.

The capability of full circuit modeling with hybrid design approach is to become more and more important over the following years with the need to study a number of microgrid and DG integrations simultaneously.

REFERENCES

[1] R. Podmore and M. R. Robinson, “The role of simulators for smart grid development,” *IEEE Trans. SmartGrid*, vol. 1, no. 2, pp. 205–212, Sep. 2010.

[2] I. Xyngi, A. Ishchenko, M. Popov, and L. van der Sluis, “Transient stability analysis of a distributed network with distributed generators,” *IEEE Trans. Power Syst*., vol. 24, no. 2, pp. 1102–1104, May 2009.

[3] R. S. Thallam, S. Suryanarayanan, G. T. Heydt, and R. Ayyanar “Impact of interconnection of distributed generation of electric distribution systems—a dynamic simulation perspective,” in Proc. IEEE Power Eng. Soc. Gen. Meet., Montreal, QC, Canada, Jun. 18–22, 2006.

[4] Z. Miao, M. A. Choudhry, and R. L. Klein, “Dynamic simulation and stability control of three-phase power distribution system with distributed generators,” in Proc. Power Eng. Soc. Winter Meet., New York, Jan. 19–22, 2002, Paper 0-7803-7322-7/02.

[5] S. T. Mak, “Propagation of transients in a distribution network,” IEEE Trans. Power Del., vol. 8, no. 1, pp. 337–343, Jan. 1993.

[6] J.A.Martinez and J.Martin-Arnedo, “Voltage sag stochastic prediction using an electromagnetic transients program,” IEEE Trans. Power Del., vol. 19, no. 4, pp. 1975–1982, Oct. 2004.

[7] B. W. Lee and S. B. Rhee, “Test requirements and performance evaluation for both resistive and inductive superconducting fault current limiters for 22.9 kV electric distribution network in Korea,” IEEE Trans. Appl. Supercond., vol. 20, no. 3, pp. 1114–1117, Jun. 2010.

[8] V. Spitsa, X. Ran, R. Salcedo, J. F. Martinez, R. E. Uosef, F. de Leon, D. Czarkowski, Z. Zabar, "On the Transient Behavior of Large-Scale Distribution Networks During Automatic Feeder Reconfiguration," *IEEE Transactions on Smart Grid*, vol.3, no.2, pp.887,896, June 2012.

[9] V. Spitsa, R. Salcedo, X. Ran, J. Martinez, R. E. Uosef, F. De León, D. Czarkowski, and Z. Zabar, “Three-phase time-domain simulation of very large distribution network,” *IEEE Trans. Power Del.*, vol. 27, no.2, pp. 677–687, Apr. 2012.

[10] L. Gérin-Lajoie and J. Mahseredjian, “Simulation of an extra-large network in EMTP: From electromagnetic to electromechanical transients,” *in Proc. Int. Conf. Power Syst. Transients (IPST)*, Kyoto, Japan, Jun. 2–6, 2009.

[11] F. de Leon, D. Czarkowski, V. Spitsa, J. A. Martinez, T. Noda, R. Iravani, X. Wang, A. Davoudi, G. W. Chang, A. Mehrizi-Sani, I. Kocar, "Development of Data Translators for Interfacing Power-Flow Programs With EMTP-Type Programs: Challenges and Lessons Learned," *IEEE Transactions on Power Delivery*, Volume: 28, Issue: 2, pp. 1192-1201, April 2013.

[12] Con Edison website http://www.coned.com

[13] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian and L. Gérin-Lajoie, “On a new approach for the simulation of transients in power systems”, *Electric Power Systems Research*, Vol. 77, Issue 11, September 2007, pp. 1514-1520.

[14] IEEE Guide for Application of Shunt Power Capacitors IEEE Std 1036-2010

[15] J. C. Das, “Analysis and Control of Large-Shunt-Capacitor-Bank Switching Transients,” IEEE Transactions on Industry Applications, Volume: 41, No: 6, pp. 1444-1451, November/September 2005.

[16] A. Greenwood, Electrical Transients in Power Systems. New York: Wiley, 1994.

[17] I. Kocar, J. Mahseredjian, U. Karaagac, G. Soykan, O. Saad, "Multiphase Load-Flow Solution for Large-Scale Distribution Systems Using MANA," IEEE Transactions on Power Delivery, vol. 29, no.2, pp. 908-915, April 2014.

[18] Bonfanti, “Shunt Capacitor Bank Switching Stresses and Tests Part 1,” Electra-182-1999.

[19] EPRI TR-106294-V2, An Assesment of Distribution System Power Quality, EPRI, Palo Alto, CA, 1996.