Unit 2.2: EMTP Simulation Approach (cont.)

Extended Example

A 100/12.47 kV, 15.0 MVA, three-phase transformer has a reactance of 8% and is connected to two capacitor banks as shown in Fig. 2.11. A switchable 300 kVAR capacitor bank (100 kVAR per-phase) is connected in parallel with the load as well as a fixed 600 kVAR capacitor bank. The two capacitors are connected by a resistance of 0.1 Ohms. Assume that this is a wye-connected, solidly-grounded system. For the comparison use the solution for the phase A voltage at the load, assuming that the capacitor bank is switched on when the phase A voltage at the load is 5 kV and is increasing. Assume that the switched capacitor bank has no initial charge stored on it.

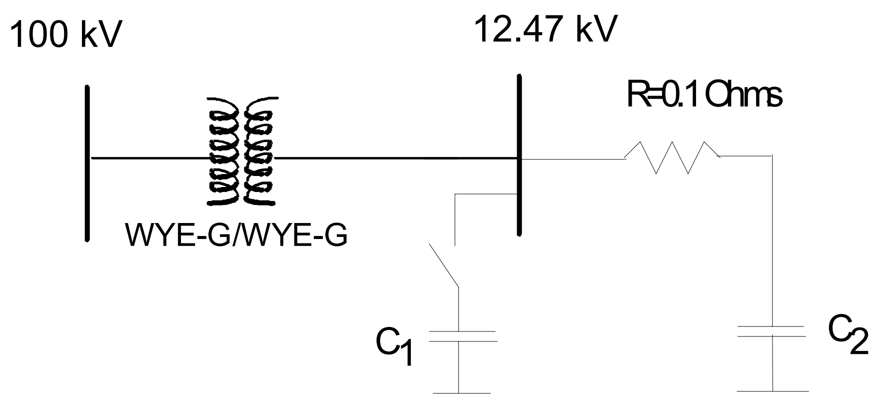

Fig. 2.11 Example System

For this particular problem, we will have the circuit model shown in Fig. 2.12.

The circuit parameters can be found to be as follows:

$$v_s(t) = 10{,}182 \sin\left(377t + 29^o\right)$$
$$L = 2.2\,mH, \quad C_1 = 5.12\,\mu F, \quad C_2 = 10.24\,\mu F, \quad R = 0.1\Omega$$
$$i_L(0) = 34.2\,A, \quad v_{C1}(0) = 0\,V, \quad v_{C2}(0) = 5000\,V$$

When the two capacitors are connected in parallel, this will result in a very fast transfer of charge between the two. The time constant associated this transfer is given by

$$\tau = R\left(\frac{C_1 C_2}{C_1 + C_2}\right) = 3.35 \times 10^{-7} \text{ sec}.$$

Hence to accurately model this transfer, we would have to have a small time step. Once the transfer of charge takes place, the two capacitors in parallel will interact with the system inductance.

This parallel capacitance in combination with the inductance will give us a natural response with a frequency of

$$\omega_o = \frac{1}{\sqrt{L\left(C_1 + C_2\right)}} = 5440\, Radians / \sec$$

which corresponds to a period of

$$T = \frac{1}{f} = \frac{2\pi}{\omega} = 1.15 \times 10^{-3} \sec.$$

The reason we want to calculate these time constants and natural frequencies is so that we can get an idea what time step will be required for an accurate simulation.

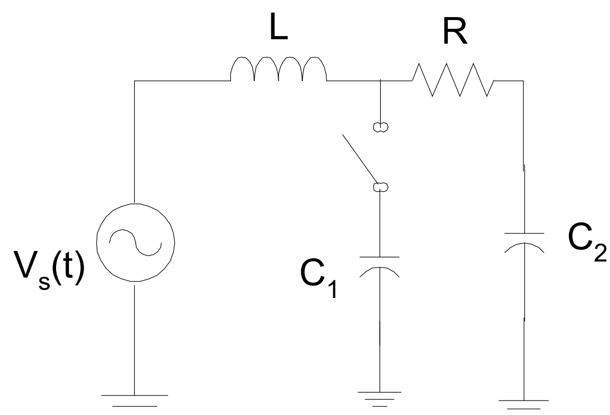

Fig. 2.12 Equivalent Circuit

To employ the EMTP modeling approach, replace the elements in Fig. 2.12 with their equivalents as derived in the previous section. This will give us the equivalent circuit shown in Fig. 2.13.

This circuit has two nodes for which we need to calculate the voltage for. Writing current law equations at each nodes results in

$$\frac{v_1(t) - v_s(t)}{2L/\Delta t} - I_{s,1}(t - \Delta t) + \frac{v_1(t)}{\Delta t / 2C_1} + I_{1,0}(t - \Delta t) + \frac{v_1(t) - v_2(t)}{R} = 0 \qquad (2.45)$$

$$\frac{v_2(t) - v_1(t)}{R} + \frac{v_2(t)}{\Delta t / 2C_2} + I_{2,0}(t - \Delta t) = 0 \qquad (2.46)$$

Equating coefficients

$$\left(\frac{1}{2L/\Delta t} + \frac{1}{\Delta t / 2C_1} + \frac{1}{R}\right) v_1(t) + \left(-\frac{1}{R}\right) v_2(t) = I_{s,1}(t - \Delta t) - I_{1,0}(t - \Delta t) + \frac{v_s(t)}{2L/\Delta t} \qquad (2.47)$$

$$\left(-\frac{1}{R}\right) v_1(t) + \left(\frac{1}{R} + \frac{1}{\Delta t / 2C_2}\right) v_2(t) = -I_{2,0}(t - \Delta t) \qquad (2.48)$$

where

$$i_{s,1}\left(t-\Delta t\right)=\frac{v_s\left(t-\Delta t\right)-v_1\left(t-\Delta t\right)}{2L/\Delta t}+I_{s,1}\left(t-2\Delta t\right) \tag{2.49}$$

$$i_{1,0}\left(t-\Delta t\right)=\frac{v_1\left(t-\Delta t\right)}{\Delta t/2C_1}+I_{1,0}\left(t-2\Delta t\right) \tag{2.50}$$

$$i_{2,0}\left(t-\Delta t\right)=\frac{v_2\left(t-\Delta t\right)}{\Delta t/2C_2}+I_{2,0}\left(t-2\Delta t\right) \tag{2.51}$$

and

$$I_{s,1}\left(t-\Delta t\right)=i_{s,1}\left(t-\Delta t\right)+\frac{\Delta t}{2L}\left(v_s\left(t-\Delta t\right)-v_1\left(t-\Delta t\right)\right) \tag{2.52}$$

$$I_{1,0}\left(t-\Delta t\right)=-i_{1,0}\left(t-\Delta t\right)-\frac{2C_1}{\Delta t}\left(v_1\left(t-\Delta t\right)\right) \tag{2.53}$$

$$I_{2,0}\left(t-\Delta t\right)=-i_{2,0}\left(t-\Delta t\right)-\frac{2C_2}{\Delta t}\left(v_2\left(t-\Delta t\right)\right) \tag{2.54}$$

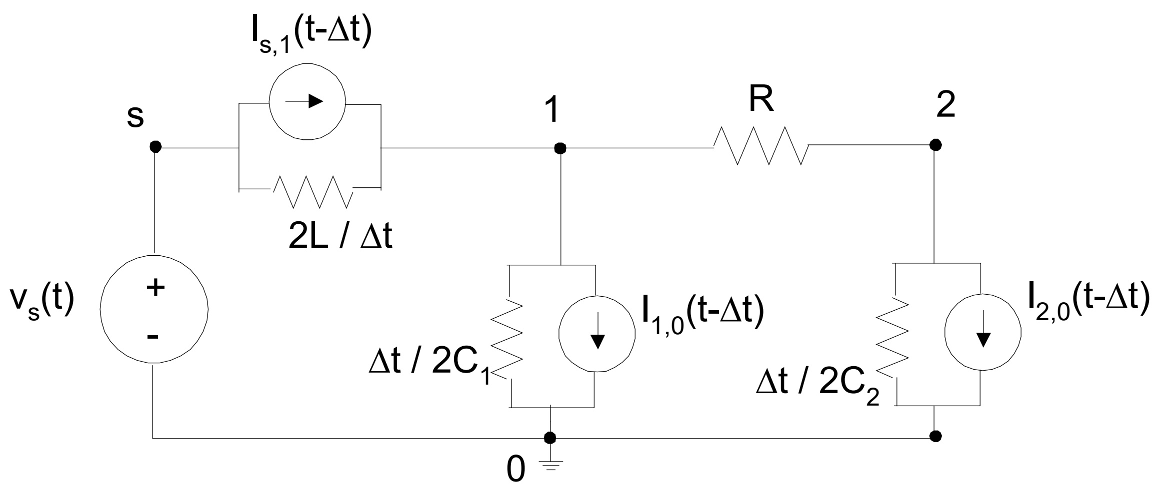

Fig. 2.13 EMTP Circuit

A copy of the Matlab code is listed below.

```
% EMTP-style Simulation
clear all;

% Set Circuit Parameters
L=.0022;
R=0.1;
C1=5.12*10^(-6);
C2=10.24*10^(-6);

% Determine Number Steps and DeltaT
Ceq=C1*C2/(C1+C2);
tal=R*Ceq;
w0=1/sqrt(L*(C1+C2));
T0=2*pi/w0;
DelT=0.01*tal;

% Look at 1 cycles of high frequency oscillation
SimTime=1*T0;

% Trapezoidal Approach

% Set Initial Conditions
Time(1)=0;
il(1)=34.2;
v1(1)=0;
v2(1)=5000;

SwAng=29.4*pi/180;
Vs(1)=10182*sin(SwAng);

% Determine initial conditions for all element currents
is1(1)=il(1);
i20(1)=(v1(1)-v2(1))/R;
i10(1)=is1(1)-i20(1);

% Calculate Admittance Matrix
Y(1,1)=(1/(2*L/DelT)+1/(DelT/(2*C1))+1/R);
Y(1,2)=-1/R;
Y(2,1)=-1/R;
Y(2,2)=(1/R+1/(DelT/(2*C2)));

tflag=0;
Tinit=0.0
t=1;
cnt=1;
while Time(t) < SimTime;

      % increment time
      t=t+1;
      cnt=cnt+1;

      % Print t every 1000 iterations
      if rem(t,1000)==0;
           t
```

```
        end;

        Time(t)=(cnt-1)*DelT+Tinit;

        % Reset time step when time=5*tal
        if (Time(t) > 5*tal) & (tflag==0);
              tflag=1;
              DelT=0.001*T0
              Tinit=Time(t-1);
              Time(t)=DelT+Tinit;
              cnt=2;
              Y(1,1)=(1/(2*L/DelT)+1/(DelT/(2*C1))+1/R);
              Y(1,2)=-1/R;
              Y(2,1)=-1/R;
              Y(2,2)=(1/R+1/(DelT/(2*C2)));
        end;

        Vs(t)=10182*sin(377*Time(t)+SwAng);

        % Calculate Current History Terms
        Is1(t-1)=is1(t-1)+(DelT/(2*L))*(Vs(t-1)-v1(t-1));
        I10(t-1)=-i10(t-1)-(2*C1/DelT)*(v1(t-1));
        I20(t-1)=-i20(t-1)-(2*C2/DelT)*(v2(t-1));

        % Calculate Current Vector
        I(1)=Is1(t-1)-I10(t-1)-Vs(t)/(2*L/DelT);
        I(2)=-I20(t-1);

        % Solve YV=I for Voltage Update
        Z=inv(Y);
        V=Z*I';
        v1(t)=V(1);
        v2(t)=V(2);

        % Update Branch Currents
        is1(t)=(Vs(t)-v1(t))/(2*L/DelT)+Is1(t-1);
        i10(t)=v1(t)/(DelT/(2*C1))+I10(t-1);
        i20(t)=v2(t)/(DelT/(2*C2))+I20(t-1);

end;

figure(1);
plot(Time,v1);
ylabel('Capacitor Voltage (Volts)');
xlabel('Time (Seconds)');
title('EMTP Approach');
```