NPTEL ONLINE CERTIFICATION COURSES

DIGITAL CONTROL IN SMPCs AND FPGA-BASED PROTOTYPING

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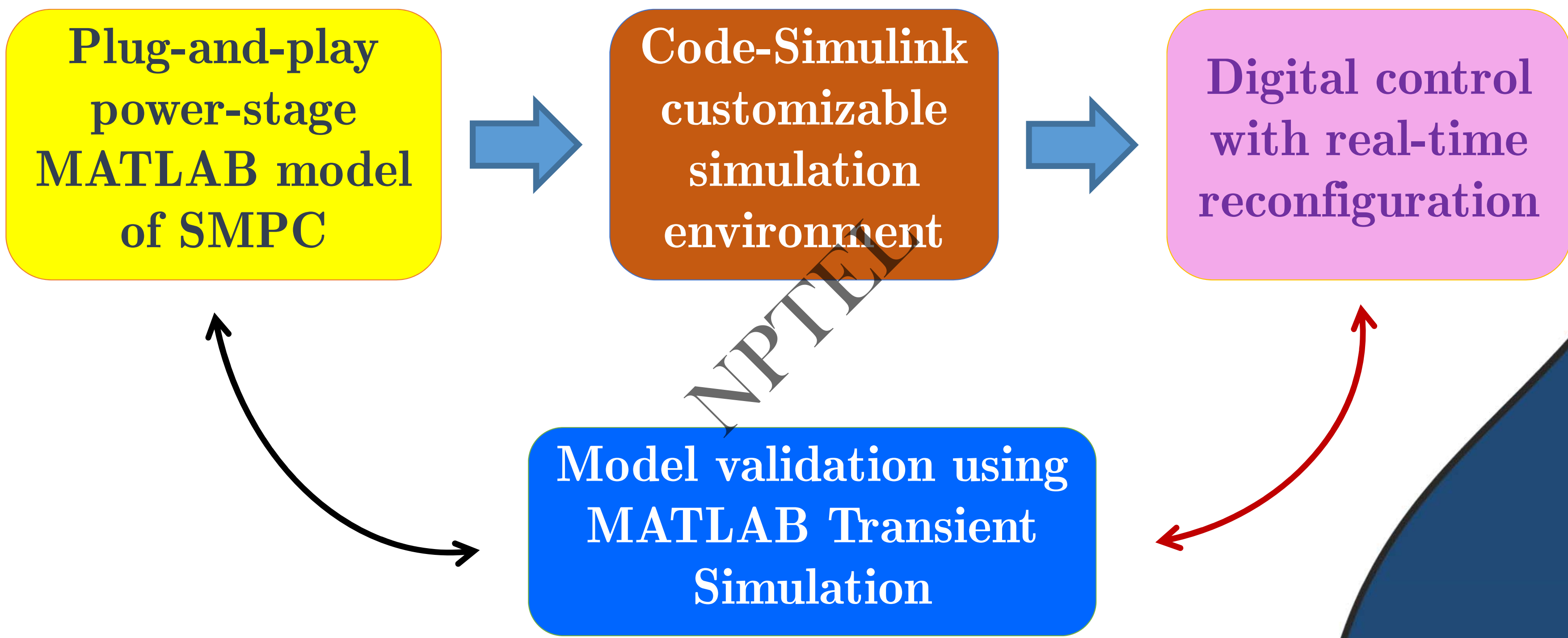
Module 04: Modeling Techniques and Mode Validation using MATLAB

Lecture 35: Validation of Discrete-Time Large-Signal Models using MATLAB – Part I

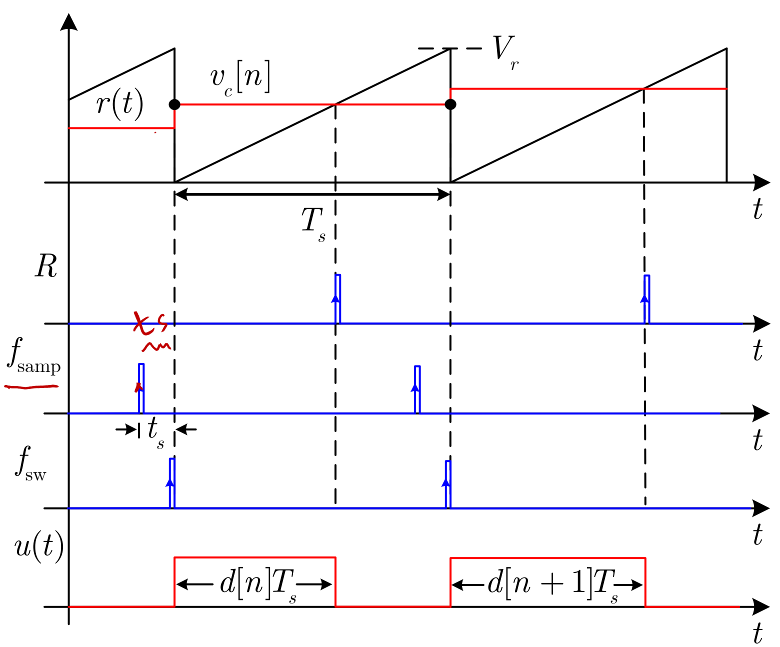
CONCEPTS COVERED

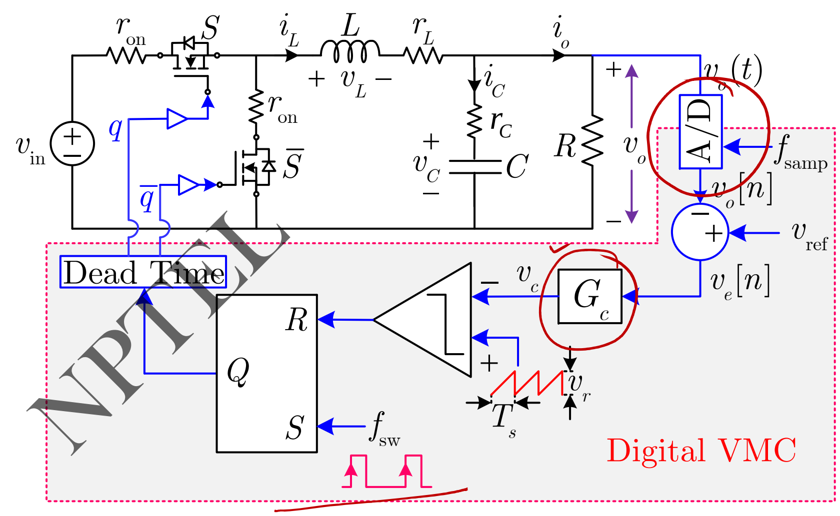
- Recall of digital control architectures and MATLAB models
- Steps for simulation using MATLAB detailed switch models and discrete-time large-signal models
- MATLAB codes and step-by-step methods for model validation
- Validation case studies using a Buck Converter

Overall Plan for MATLAB based Validation

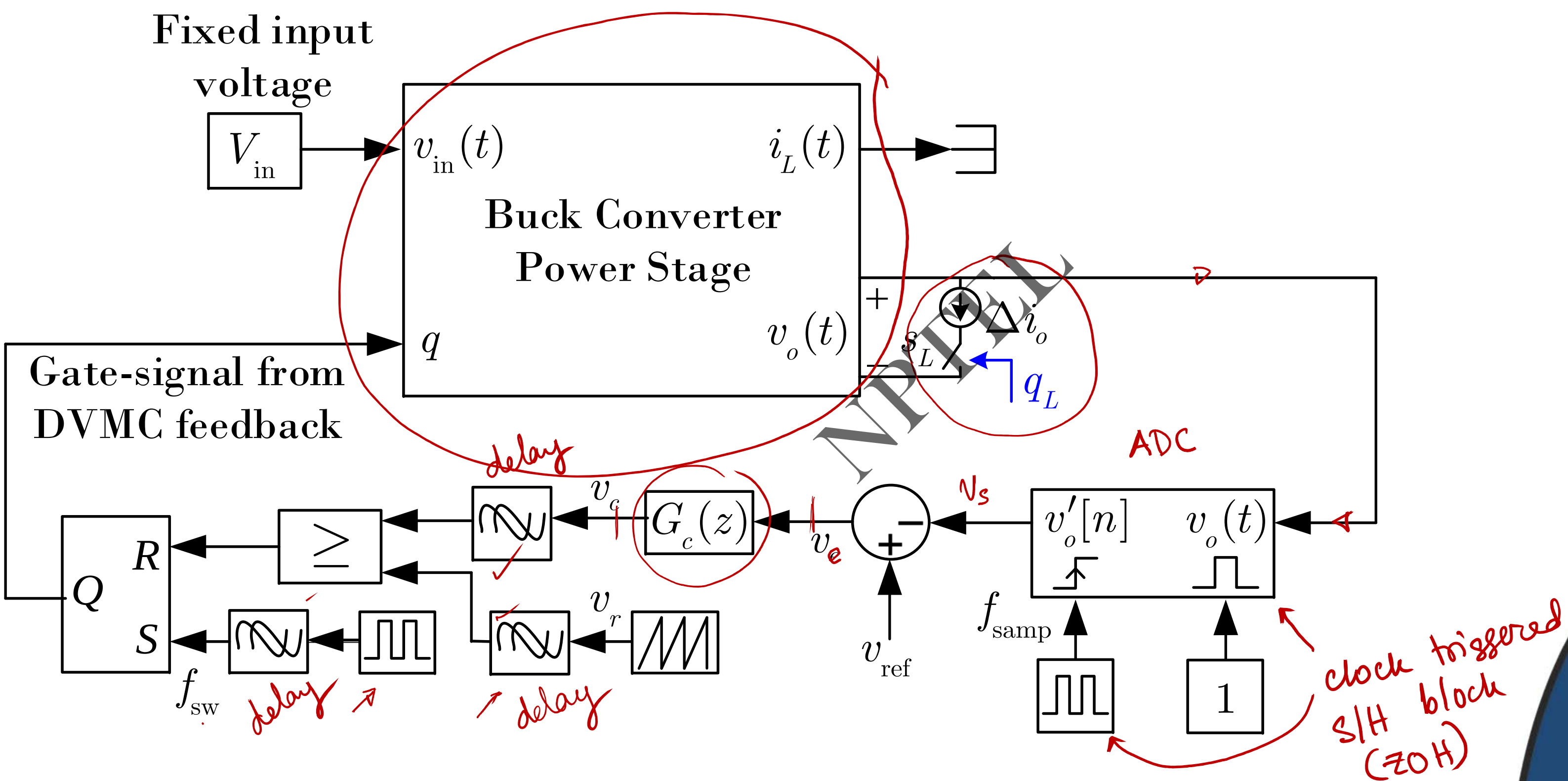


Digital Voltage Mode Control (DVMC) of Buck Converter





Device Under Test (DUT) for Validation of DT Large-Signal Model



Validation of DT Large-Signal Model under Closed Loop

a) Using actual switch simulation

1. Provide initial conditions for $v_C(t)$ and $i_L(t)$
2. Do not turn on S_L for 1 ms and let the converter reach steady-state
3. Apply a load step
4. Capture time domain data and store as v_o and i_L

Validation of DT Large-Signal Model under Closed Loop (contd…)

b) Using DT large-signal model

1. Provide initial conditions for $v_C(t)$ and $i_L(t)$ same as those in switch simulation

R_1

2. Let the DT large-signal model run for 1 ms

3. Capture $v_o(t)$ and $i_L(t)$ as the state variables throughout the simulation time

Validation of DT Large-Signal Model under Closed Loop (contd…)

b) Using DT large-signal model

4. Change the load resistance at 1 ms to emulate a load step
5. Capture $v_o(t)$ and $i_L(t)$ as state variables for every sampling cycle throughout the simulation run time
6. Compare the captured data of v_o & i_L for DT large-signal validation

Steps to Verify Large-Signal DT Model using MATLAB

buck_conv_DVMC_simulation.m

```
clear; close all; clc;
%% Setting parameters
buck_parameter;
DCM_En=0;
N_tran=500; T_tran=2*N_tran*T;
t_start=0;  t_sim=T_tran;
%% Controller parameters
Kp=10;   Ki=0.3;  Kd=20;  t_s=0.1*T;
V_m=10;   R1=1;  R2=0.05; R=R1;

I_L_int=1;  V_c_int=0.99;
V_s_int=V_c_int; V_integral=0;
……
```

buck_parameter.m

```
L=0.5e-6;       % output inductance
C=200e-6;       % output capacitance
T=2e-6;         % switching time period
r_L=5e-3;       % inductor DCR
v_d=0.55;       % diode voltage drop
r_1=5e-3;       % HS MOS on resistance
r_d=5e-3;       % LS MOS on resistance
r_C=3e-3;       % capacitor ESR
Vin=12;         % input voltage
Vref=1;         % ref. output voltage
Io_max =20;     % max. load current
```


$N_{tran} \times T$

R_1 R_2

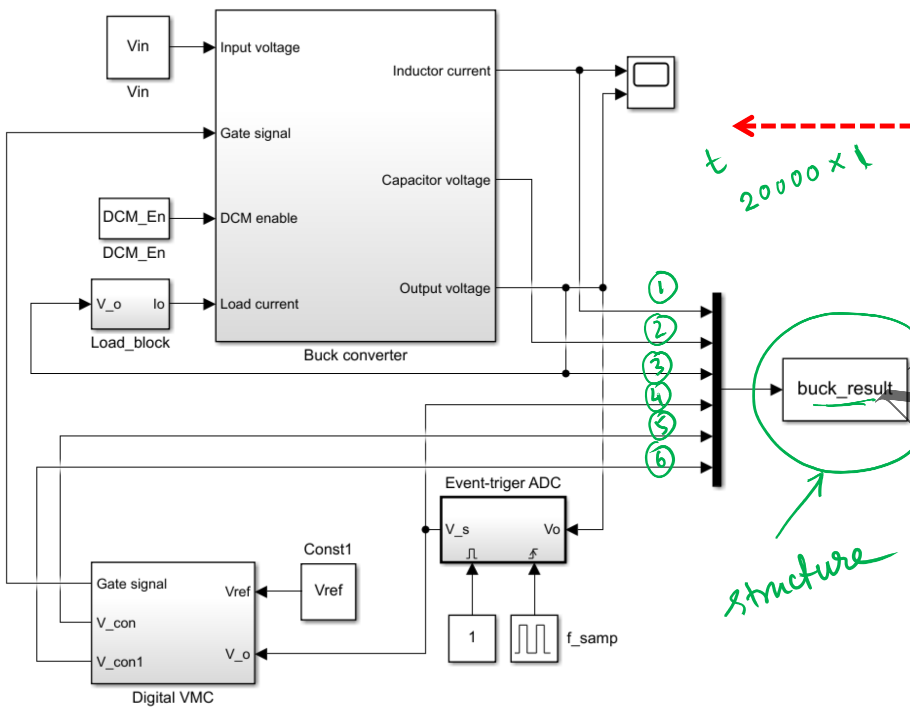
$N_{tran} \times T$

T_{tran}

$R_2 = 0.05\Omega$

$i_{o2} = \frac{V_o}{R_2}$

Steps to Verify Large-Signal DT Model using MATLAB (contd…)



buck_conv_DVMC_simulation.m

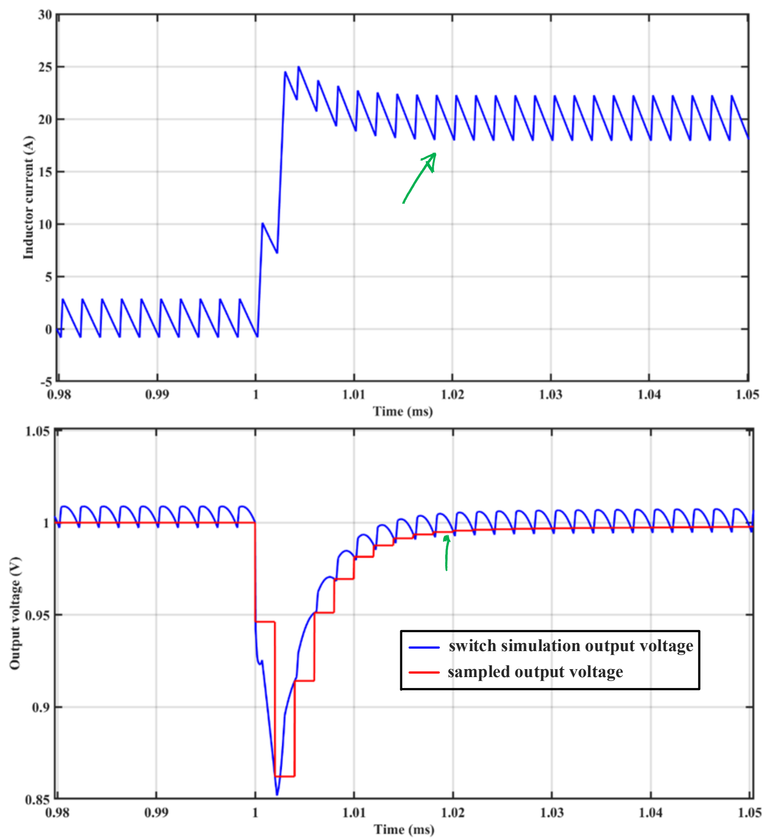
```
……
sim('buck_converter_DVMC.slx');

t=buck_result.time; t_scale=t*1e3;
x=buck_result.data; i_L=x(:,1);
V_cap=x(:,2); V_o=x(:,3);
V_s=x(:,4); V_n=x(:,5); Vr_d=x(:,6);
%% Plot subroutine
plot_buck_simulation;
```

20000 x 6

x

t	Ch1	Ch2
	$i_L(t)$	$V_c(t)$
0		
Δt_1		
$\Delta t_1+\Delta t_2$		

Steps to Verify Large-Signal DT Model using MATLAB (contd…)



buck_conv_DVMC_simulation.m

```
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sim('buck_converter_DVMC.slx');

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x=buck_result.data;  i_L=x(:,1);
V_cap=x(:,2); V_o=x(:,3);
V_s=x(:,4); V_n=x(:,5); Vr_d=x(:,6);
%% Plot subroutine
plot_buck_simulation;
```

Steps to Verify Large-Signal DT Model using MATLAB (contd…)

buck_DT_LSM_TE.m

```
clc;
buck_parameter;
Kp=10;  Ki=0.3;  Kd=20;
t_s=0.1*T;  V_m=10;  R1=1;
R2=0.05; R=R1; N_tran=500;

buck_DT_model_matrices;

……
```

buck_DT_model_matrices.m

```
alpha=R/(R+r_C);  r_e=(r_l+r_L);
T_s=t_s;  I_den=[1 0; 0 1];
%% Define system, input and output matrices
A_on=[-(r_e+(alpha*r_C))/L      -alpha/L;
                alpha/C              -alpha/(R*C)];
A_off=A_on;  B=[1/L; 0];
C_m=[r_C*alpha alpha];
```

$$A_{on} = A_{off} = \begin{bmatrix} -\frac{(r_e+\alpha r_c)}{L} & -\frac{\alpha}{L} \\ \frac{\alpha}{C} & -\frac{\alpha}{R_C} \end{bmatrix}$$

$$C_0 = [\alpha r_c \quad \alpha]$$

Steps to Verify Large-Signal DT Model using MATLAB (contd…)

buck_DT_LSM_TE.m

```
……
i_L_n=I_L_int; v_cap_n=V_c_int;
x_n=[i_L_n; v_cap_n];
V_o_s=C_m*x_n; Vsam=v_cap_n;
V_intg_int=0; Ve_int=0;
t1=0; t1_scale=t1*1e3;

figure(1)
plot(t1_scale,x_n(1),'o','Linewidth', 2); hold on; grid on;

figure(2)
plot(t1_scale,Vsam,'o','Linewidth', 2); hold on; grid on;
……
```

Steps to Verify Large-Signal DT Model using MATLAB (contd…)

N_{tran}

0 to $N_{tran} - 1$

buck_DT_dynamics.m

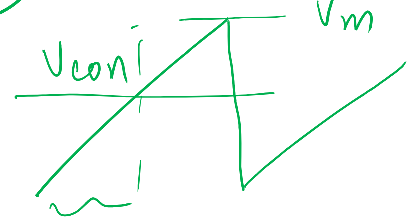
```
for n=0:N_tran-1
  figure(2)
  plot(t1_scale,Vsam,'o','Linewidth', 2);   hold on; grid on;
  Ve=(Vref-Vsam);
  V_intg=V_intg_int+(Ki*Ve);   V_intg_int=V_intg;
  V_der=Kd*(Ve-Ve_int);    Ve_int=Ve;
  Vcon=(Kp*Ve)+V_intg+V_der;    D_temp=Vcon/V_m;

    if D_temp<0
       D=0;
    elseif D_temp>1
       D=1;
……
```


buck_DT_LSM_TE.m

```
……
%% DT Large-Signal Model
buck_DT_dynamics;
R=R2;  N_tran=500;
buck_DT_model_matrices;
V_o_s=C_m*x_n;
Vsam= V_o_s;
buck_DT_dynamics;
```

$D = \frac{V_{con}}{V_m}$



Steps to Verify Large-Signal DT Model using MATLAB (contd…)

buck_DT_dynamics.m

```
……
    else
       D=D_temp;
    end

  A_LS=(expm(A_on*T));
  B_LS=(expm(A_on*(T-(D*T)-T_s)))*((expm(A_on*(D*T)))-I_den)*(inv(A_on))*B;
  x_n1=A_LS*x_n+B_LS*Vin;
  t1=t1+T;  t1_scale=t1*1e3;
  x_n=x_n1; V_o_s=C_m*x_n;  Vsam= V_o_s;
  figure(1)
  plot(t1_scale,x_n(1),'o','Linewidth', 2);    hold on; grid on;
end
```

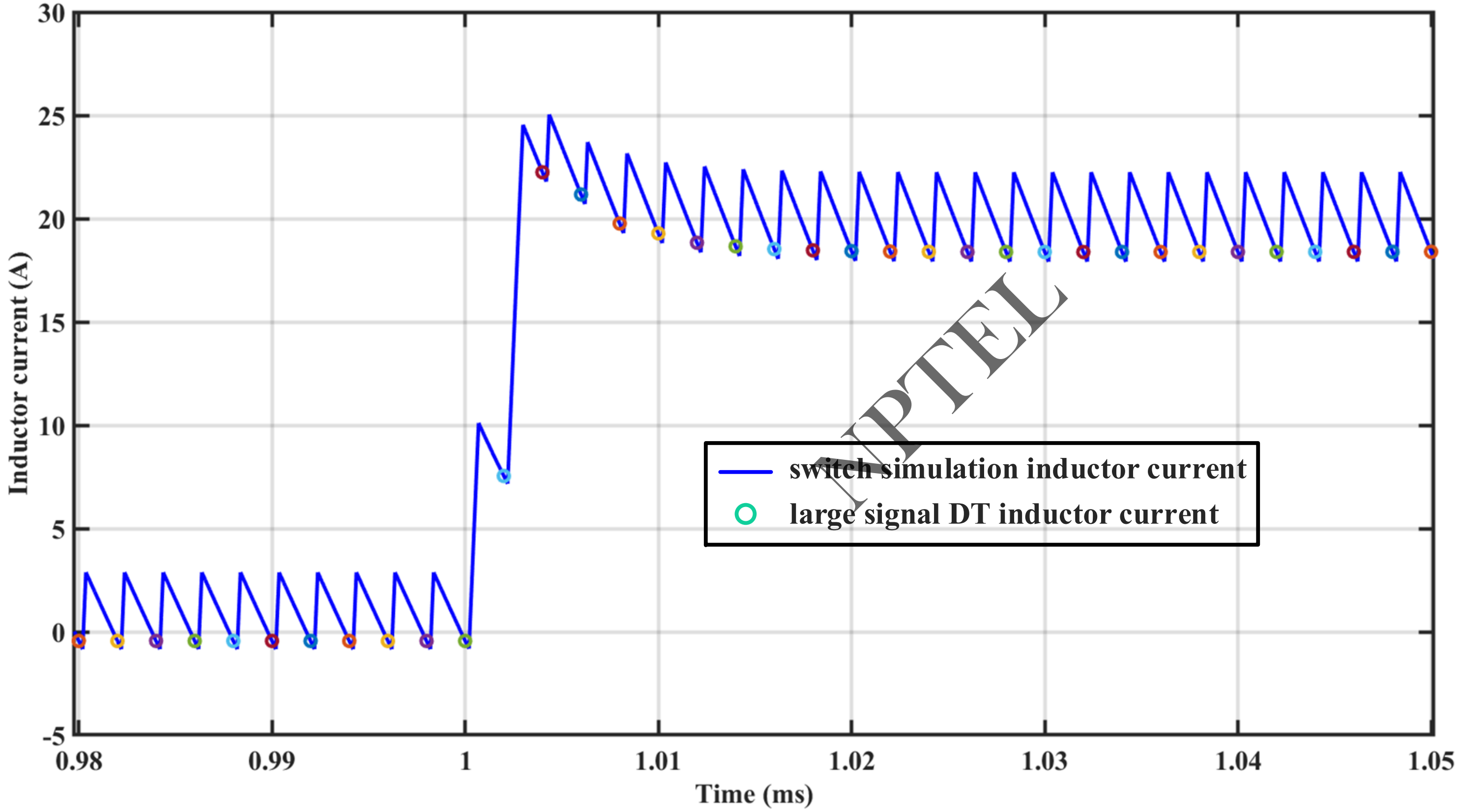
$x_{n+1} = A_{eq} x_n + B_{eq} V_{in}$

$A_{eq} = e^{A_{on}T}$

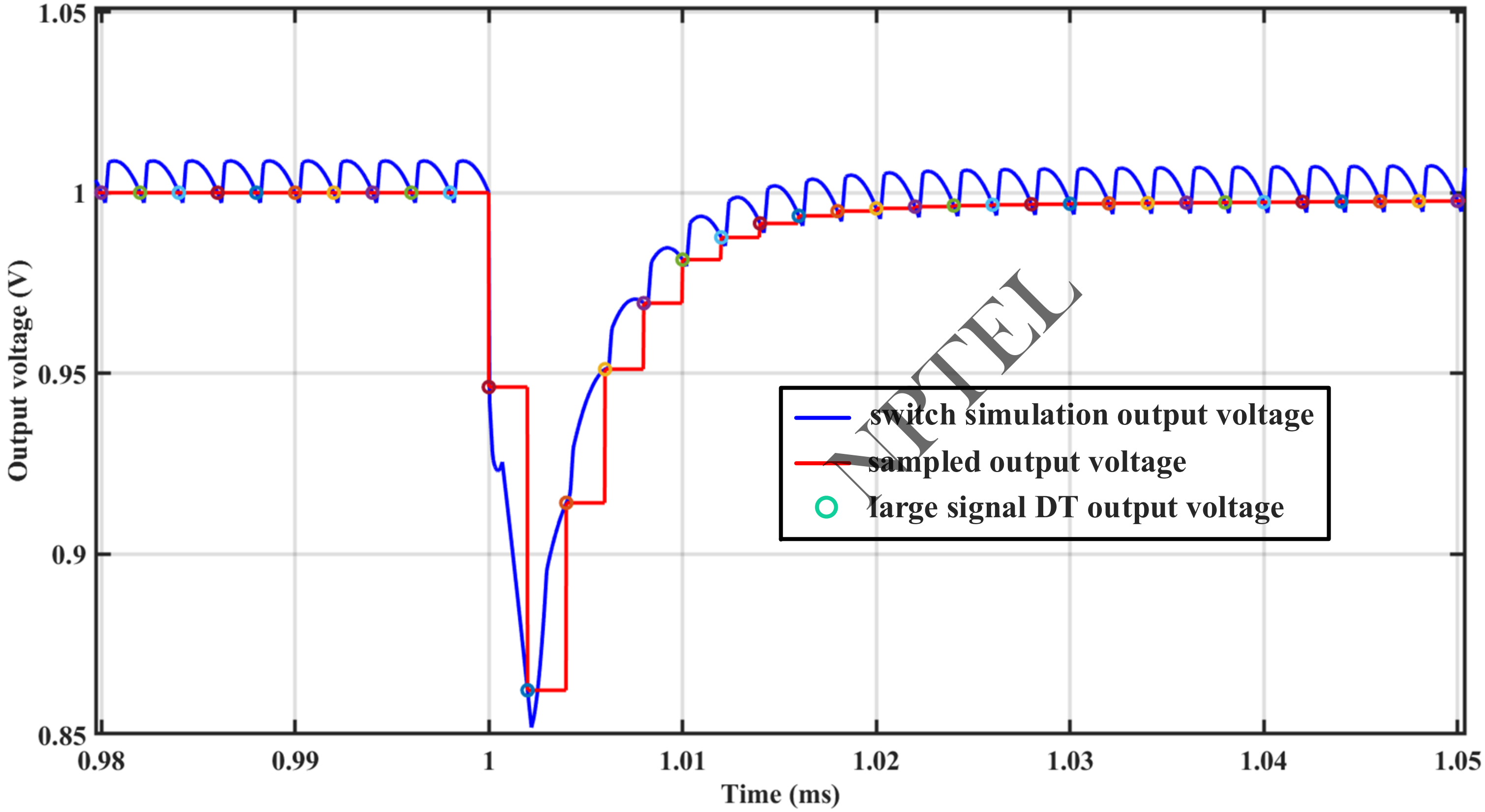
$\text{expm}(A_{on}T)$

$B_{eq} = e^{A_{on}(T-DT-t_s)} \cdot \left[e^{A_{on}DT} - I\right] A^{-1} B$

Steps to Verify Large-Signal DT Model using MATLAB (contd…)



Steps to Verify Large-Signal DT Model using MATLAB (contd...)



CONCLUSION

- Recall of digital control architectures and MATLAB models
- Steps for simulation using MATLAB detailed switch models and discrete-time large-signal models
- MATLAB codes and step-by-step methods for model validation
- Validation case studies using a Buck Converter

THANK YOU !