Network Theory

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Gyan Ranjan Biswal received his B.E. in Electronics Engineering from the Pt. Ravishankar Shukla University, India in 1999 and M. Tech. (Honors) in Instrumentation & Control Engineering from the Chhattisgarh Swami Vivekananda Technical University, India in 2009 followed by Ph.D. in Electrical Engineering, specialized in the area of Power System Instrumentation (Power Generation Automation) from the Indian Institute of Technology Roorkee, India in 2013.

He is expertise in Design and Development of cooling systems for large size electrical generators, and the C&I of process industries. He has been in academia for about twelve years. Presently, he is with VSS University of Technology, Burla, India at the capacity of Head and Associate Professor, EEE from Dec. 2016. He has more than 65 publications in various Journals and Conferences of Internationally repute to his credit. He also holds a patent as well, and filed one more. He also adapted one international edition book published by Pearson India. He received research grants of US$90,000 (INR 50 lakhs). He has been supervised 09 Masters' theses, and registered 04 PhD theses. He has also been recognized with many national and international awards by elite bodies. He has been awarded with CICS award under the head of Indian National Science Academy for travel support to USA, MHRD Fellowship by Govt. of India, and Gopabandhu Das Scholarship in his career. His major areas of interests are Power System Instrumentation, Industrial Automation, Robust and Intelligent Control, the Smart Sensors, IoT enabled Smart Sensors, the Smart Grid, Fuel Cell lead Sustainable Sources of Energy, and System Reliability.

Dr. Biswal is a Fellow IE (India), Senior Member of IEEE, USA, and Life Member of ISTE, India. He is actively involved in review panels of different societies of international repute viz. IEEE, IFAC, and the ISA. Currently, he is also actively involved as a Member of IEEE–SA (Standards Association) working groups; IEEE P1876 WG, IEEE P21451-001 WG, and IEEE P1415. He has also been invited for delivering guest lectures at World Congress on Sustainable Technologies (WCST) Conf. 2012, London, UK, INDICON 2015, New Delhi, India, National Power Training Institute (NPTI), Nangal, India, and G.B. Pant Engineering College, Pauri, Gharwal, India, Surendra Sai University of Technology (formerly UCE), Burla, and as a guest expert in 2016 IEEE PES General Meeting Boston, MA, USA.

Syllabus

Network Theory

MODULE-I (9 HOURS) [Online mode: 5 HOURS + 1 Test]

Analysis of Coupled Circuits: Self-inductance and Mutual inductance, Coefficient of coupling, Series connection of coupled circuits, Dot convention, Ideal Transformer, Analysis of multi-winding coupled circuits, Analysis of single tuned and double tuned coupled circuits.

Transient Response: Transient study in series RL, RC, and RLC networks by time domain and Laplace transform method with DC and AC excitation. Response to step, impulse and ramp inputs of series RL, RC and RLC circuit.

MODULE-II (7 HOURS) [Online mode: 5 HOURS + 1 Test]

Two Port networks: Types of port Network, short circuit admittance parameter, open circuit impedance parameters, Transmission parameters, Condition of Reciprocity and Symmetry in two port network, Inter-relationship between parameters, Input and Output Impedances in terms of two port parameters, Image impedances in terms of ABCD parameters, Ideal two port devices, ideal transformer. Tee and Pie circuit representation, Cascade and Parallel Connections.

MODULE-III (8 HOURS) [Online mode: 5 HOURS + 1 Test]

Network Functions & Responses: Concept of complex frequency, driving point and transfer functions for one port and two port network, poles & zeros of network functions, Restriction on Pole and Zero locations of network function, Time domain behavior and stability from pole-zero plot, Time domain response from pole zero plot.

Three Phase Circuits: Analysis of unbalanced loads, Neutral shift, Symmetrical components, Analysis of unbalanced system, power in terms of symmetrical components.

MODULE-IV (9 HOURS) [Online mode: 5 HOURS + 1 Test]

Network Synthesis: Realizability concept, Hurwitz property, positive realness, properties of positive real functions, Synthesis of R-L, R-C and L-C driving point functions, Foster and Cauer forms.

MODULE-V (6 HOURS) [Online mode: 5 HOURS + 1 Test]

Graph theory: Introduction, Linear graph of a network, Tie-set and cut-set schedule, incidence matrix, Analysis of resistive network using cut-set and tie-set, Dual of a network.

Filters: Classification of filters, Characteristics of ideal filters.

Text and Reference Books

Recommended Text Books:

1. "Introductory Circuit Analysis", Robert L. Boylestad, Pearson, 12th ed., 2012.
2. "Network Analysis", M. E. Van Valkenburg, Pearson, 3rd ed., 2006.
3. "Engineering Circuit Analysis", W. Hayt, TMH, 2006.
4. "Network Analysis & Synthesis", Franklin Fa-Kun. Kuo, John Wiley & Sons.

Reference Books:

* "Basic Circuit Theory, Huelsman, PHI, 3rd ed.,
* "HUGHES Electrical and Electronic Technology", Revised by J. Hiley, K. Brown, and I. M. Smith, Pearson, 10th ed., 2011.
* "Circuits and Networks", Sukhija and Nagsarkar, Oxford Univ. Press, 2012.
* "Fundamentals of Electric Circuits", C. K. Alexander and M. N. O. Sadiku, McGraw-Hill Higher Education, 3rd ed., 2005.
* "Fundamentals of Electrical Engineering", L. S. Bobrow, Oxford University Press, 2nd ed., 2011.
* "Circuit Theory (Analysis and Synthesis)", A. Chakrabarti, Dhanpat Rai pub.

Other Important References

Reference Sites:	
1.	NPTEL, The National Programme on Technology Enhanced Learning (NPTEL): https://nptel.ac.in/
2.	MIT OpenCourseWare : https://ocw.mit.edu/index.htm

Course Outcomes

Upon successful completion of this course, you (students) will be able to

CO1	Analyze coupled circuits and understand the difference between the steady state and transient response of 1st and 2nd order circuit and understand the concept of time constant.
CO2	Learn the different parameters of two port network.
CO3	Concept of network function and three phases circuit and know the difference of balanced and unbalanced system and importance of complex power and its components.
CO4	Synthesis the electrical network.
CO5	Analyse the network using graph theory and understand the importance of filters in electrical system.

Network Synthesis Technique: Basic Properties

* $H(s) = \frac{P(s)}{Q(s)} = \frac{a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n}{b_0 s^m + b_1 s^{m-1} + \cdots + b_{m-1} s + b_m}$ ——— (1)

  $Q(s)$ → Hurwitz polynomial.

* $Re[H(j\omega)] \geq 0$ for all values of ω

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* Basic Philosophy of Synthesis

  ↓

  each function represents single element R, L & C

  or a suitable realized combination of R, L & C.

$$Z(s) = \frac{a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n}{b_0 s^m + b_1 s^{m-1} + \cdots + b_{m-1} s + b_m}$$ ——— (2)

Methods

(i) removal of a pole at ∞.

(ii) removal of a pole at origin.

(iii) removal of conjugate imaginary poles, and

(iv) removal of a constant.

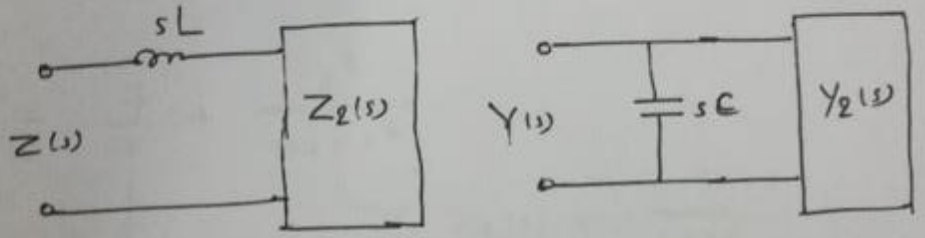
(i) removal of 'a Pole at ∞'

(2)

$Z(s) \longrightarrow n - m = 1$ ★

+ $\frac{a_0}{b_0} s$ divides $H(s)$ by $D(s)$

$$Z(s) = \frac{a_0}{b_0} s + Z_2(s) \qquad \text{——— (1)}$$



B Impedance

Admittance

★ i.e. a 'L' will taken out for Z(s) network / a 'C' will taken out for Y(s) network

(ii) removal of 'a Pole at 0'

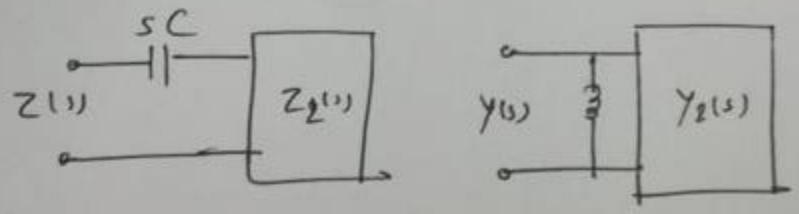
+ taking s common from denominator

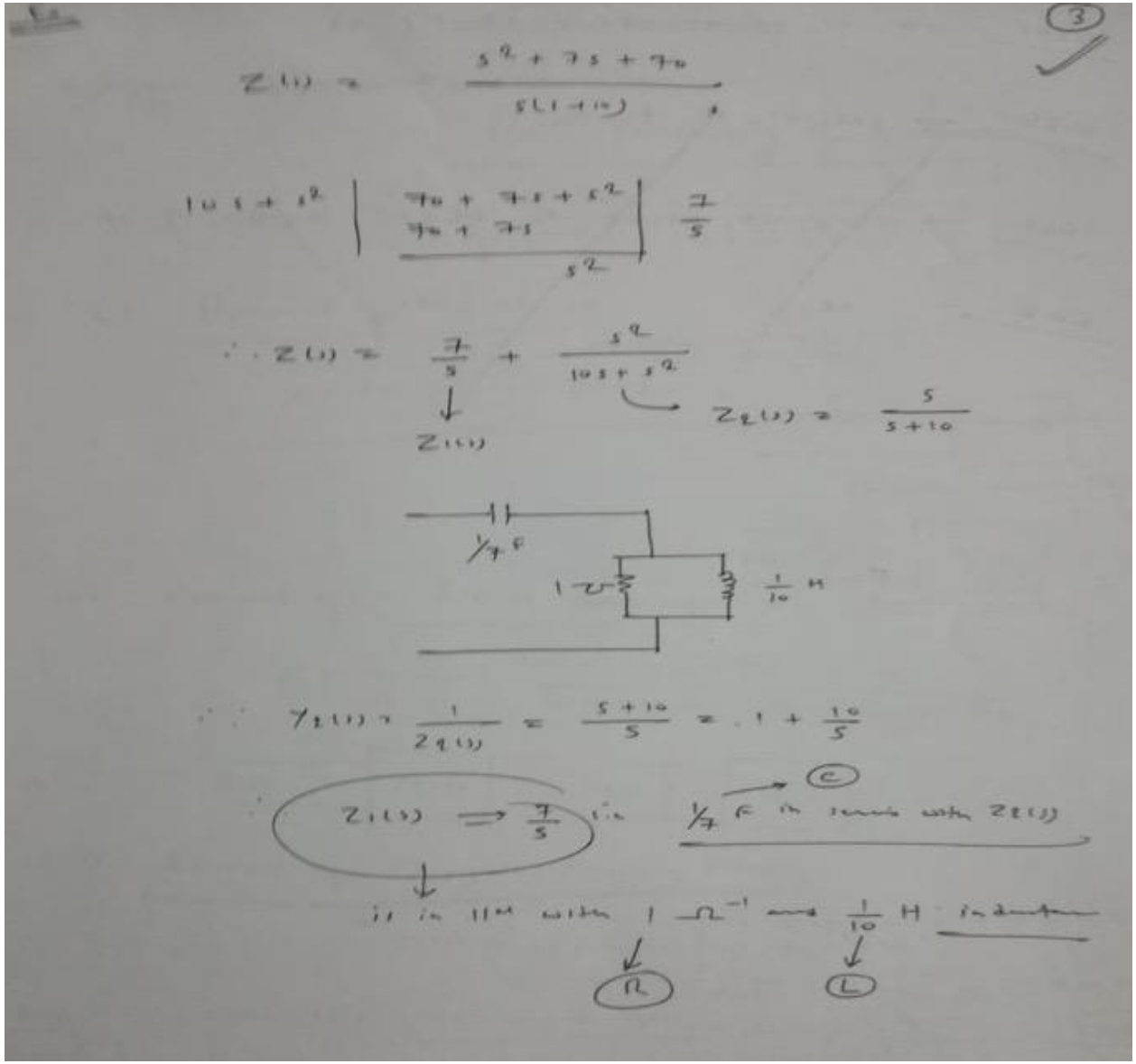
$$Z(s) = \frac{k_0}{s} \cdot \frac{c_0 s^{n-1} + \cdots + c_{n-1}}{b_{n-1} + b_{n-2} \cdots}$$

$$Z(s) = Z_1(s) \cdot Z_2(s) \quad \text{---} \quad (2)$$

Here $Z_1(s) = \frac{k_0}{s}$ represents a capacitor 'C' in case of $Z(s)$

that a 'L' in case of $Y(s)$




3
$Z(s) = \frac{s^2 + 7s + 70}{s(s+10)}$
$10s + s^2 \;|\; 70 + 7s + s^2 \;|\; \frac{7}{s}$
$70 + 7s$
s^2
$\therefore Z(s) = \frac{7}{s} + \frac{s^2}{10s + s^2}$
$Z_1(s)$
$Z_2(s) = \frac{s}{s+10}$
$\frac{1}{7}$ F
1 Ω
$\frac{1}{10}$ H
$Y_2(s) = \frac{1}{Z_2(s)} = \frac{s+10}{s} = 1 + \frac{10}{s}$
$Z_1(s) \rightarrow \frac{7}{s}$ i.e. $\frac{1}{7}$ F in series with $Z_2(s)$
C
it is in ||el with 1 Ω^{-1} and $\frac{1}{10}$ H inductor
R
L

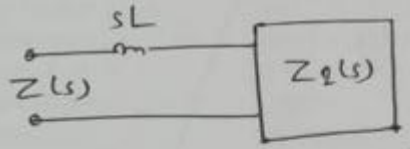
Basic Philosophy of Synthesis

$$Z(s) = \frac{a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n}{b_0 s^m + b_1 s^{n-1} + \cdots + b_{m-1} s + b_m}$$

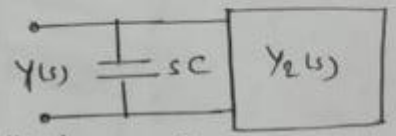
(i) Removal of a pole at ∞

indicate that a 'L' should be taken out in series

$$Z(s) = \frac{a_0}{b_0} s + Z_2(s)$$



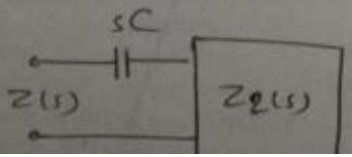
Impedance network $Z(s)$

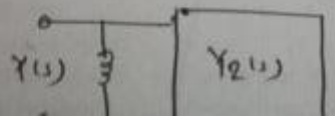


Admittance network

(ii) Removal of a Pole at ~~Zero~~ Origin ('0')

$$Z(s) = \frac{k_0}{s} \cdot \frac{c_0 s^{n-1} + c_1 s^{n-2} + \cdots + c_{n-1}}{b_{m-1} + b_{m-2} + \cdots + b_1 s^{n-2} + b_0 s^{n-1}}$$





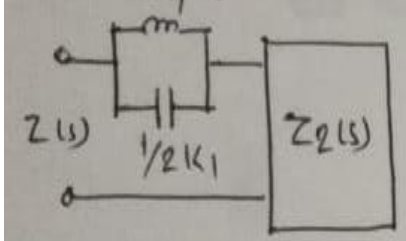
(iii) Removal of Conjugate Imaginary Poles

i.e. $Z(s)$ has pole at $s = \pm j\omega_1$

$$Z_1(s) = (s+j\omega_1)(s-j\omega_1) = s^2+\omega_1^2$$

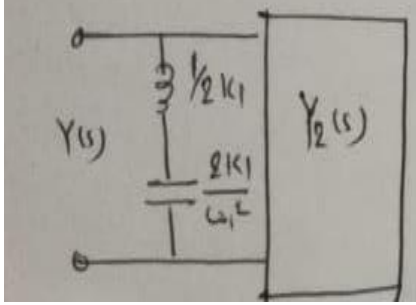
$$\text{i.e. } Z(s) = \frac{P(s)}{(s^2+\omega_1^2)Q_1(s)} = \frac{2K_1 s}{s^2+\omega_1^2} + Z_2(s)$$

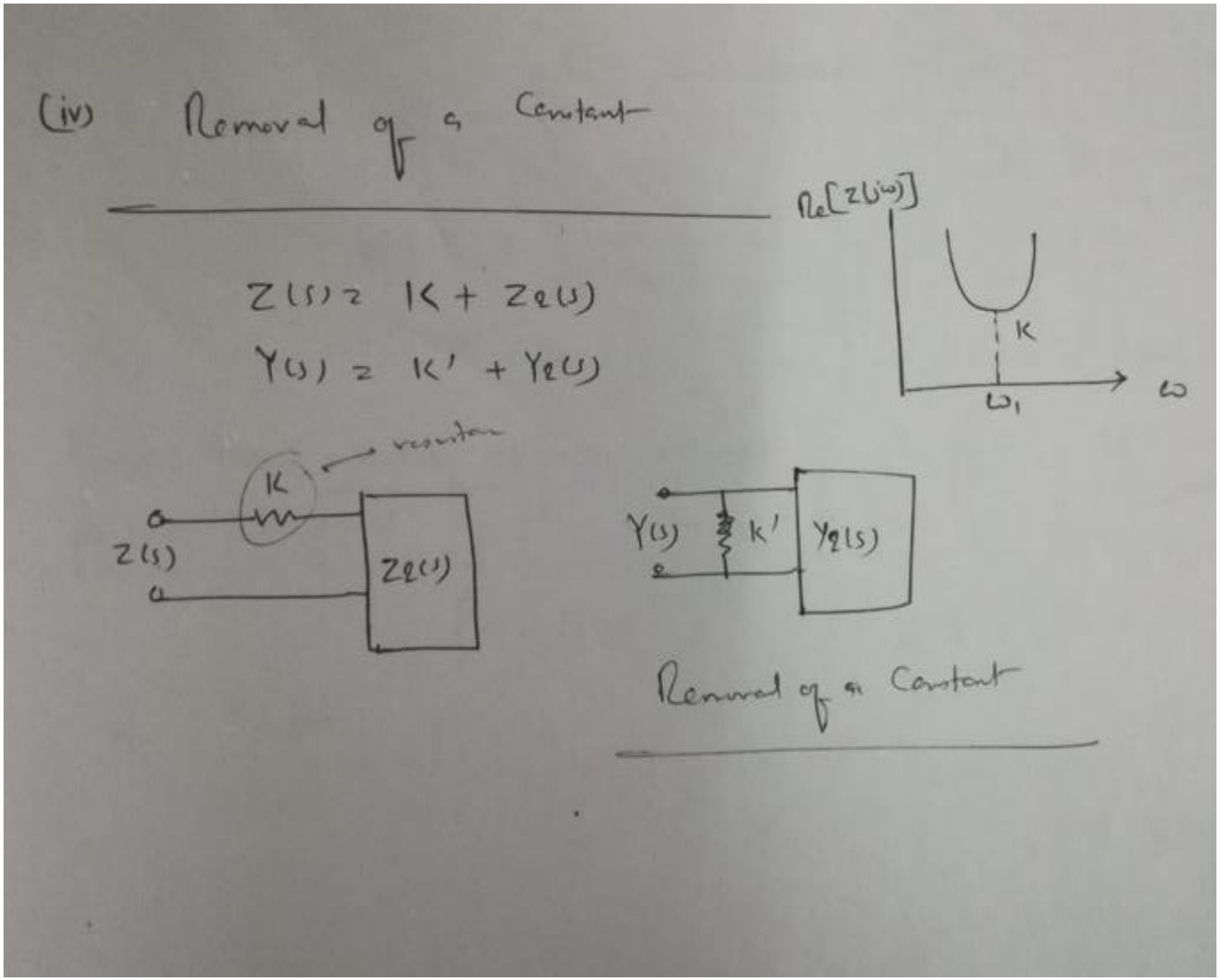
now if 'L & C' are in $\|^{el}$ $= (L\|C) \neq \frac{1/C\, s}{s^2+\frac{1}{LC}} = \frac{2K_1 s}{s^2+\omega_1^2}$ — (1)

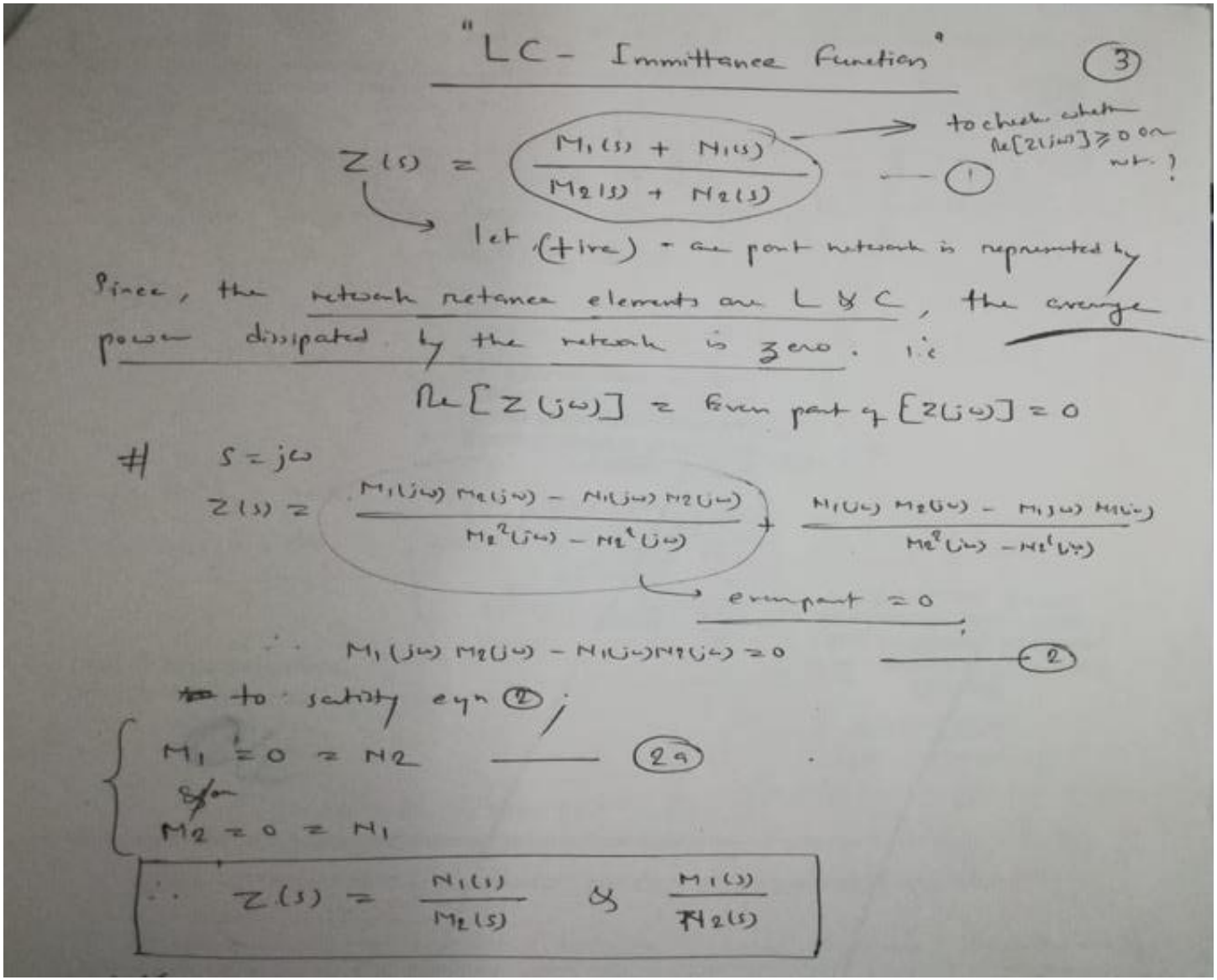


$$\therefore C = \frac{1}{2K_1} \text{ & } L = \frac{2K_1}{\omega_1^2}$$

i.e. $L\|C$ → is in series with $Z_2(s)$




(iv) Removal of a Constant
$Z(s) = K + Z_2(s)$
$Y(s) = K' + Y_2(s)$
$Re[Z(j\omega)]$
K
ω_1
ω
resistor
K
Z(s)
$Z_2(s)$
Y(s)
K'
$Y_2(s)$
Removal of a Constant


"LC - Immittance Function"
3
$Z(s) = \frac{M_1(s) + N_1(s)}{M_2(s) + N_2(s)}$ — (1)
to check whether $Re[Z(j\omega)] \geq 0$ or not?
let (+ive) - a part network is represented by
Since, the network reatance elements are L & C, the average power dissipated by the network is zero. i.e
$Re[Z(j\omega)]$ = Even part of $[Z(j\omega)] = 0$
$s = j\omega$
$Z(s) = \frac{M_1(j\omega) M_2(j\omega) - N_1(j\omega) N_2(j\omega)}{M_2^2(j\omega) - N_2^2(j\omega)} + \frac{N_1(j\omega) M_2(j\omega) - M_1(j\omega) N_1(j\omega)}{M_2^2(j\omega) - N_2^2(j\omega)}$
even part = 0
$M_1(j\omega) M_2(j\omega) - N_1(j\omega) N_2(j\omega) = 0$ — (2)
to satisfy eqn (2);
$M_1 = 0 = N_2$ — (2a)
or
$M_2 = 0 = N_1$
$\therefore Z(s) = \frac{N_1(s)}{M_2(s)}$ & $\frac{M_1(s)}{N_2(s)}$

Classifications of Network Synthesis

- LC – Immittance Function
- RC Impedance Function and RL Admittance Function
- RL Impedance Function and RC Admittance Function

- Foster Form – I (FF – I)
- Foster Form – II (FF – II)
- Cauer Form – I (CF – I)
- Cauer Form – II (CF – II)

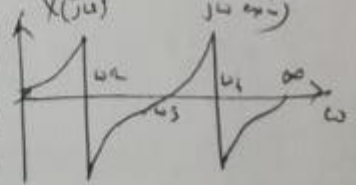
Conditions

It is a

(i) ratio of even to odd / odd to even polynomials.

(ii) It has poles & zeros of $Z(s)/Y(s)$ on the imaginary axis.

(iii) The poles & zeros interlace on the jω-axis. (i.e. $x \neq 0$; alternate on the jω axis)



Ex. 1

* Sign

① the highest and the lowest power of $N(s)$ & $D(s)$ differ by unity. ($n - m = 1$)

② at $s=0$ & at $s=\infty$, a critical freq. is always present whether a zero / a pole.

$$Z(s) = \frac{K_s(s^2+\omega_3^2)}{(s^2+\omega_2^2)(s^2+\omega_4^2)}$$

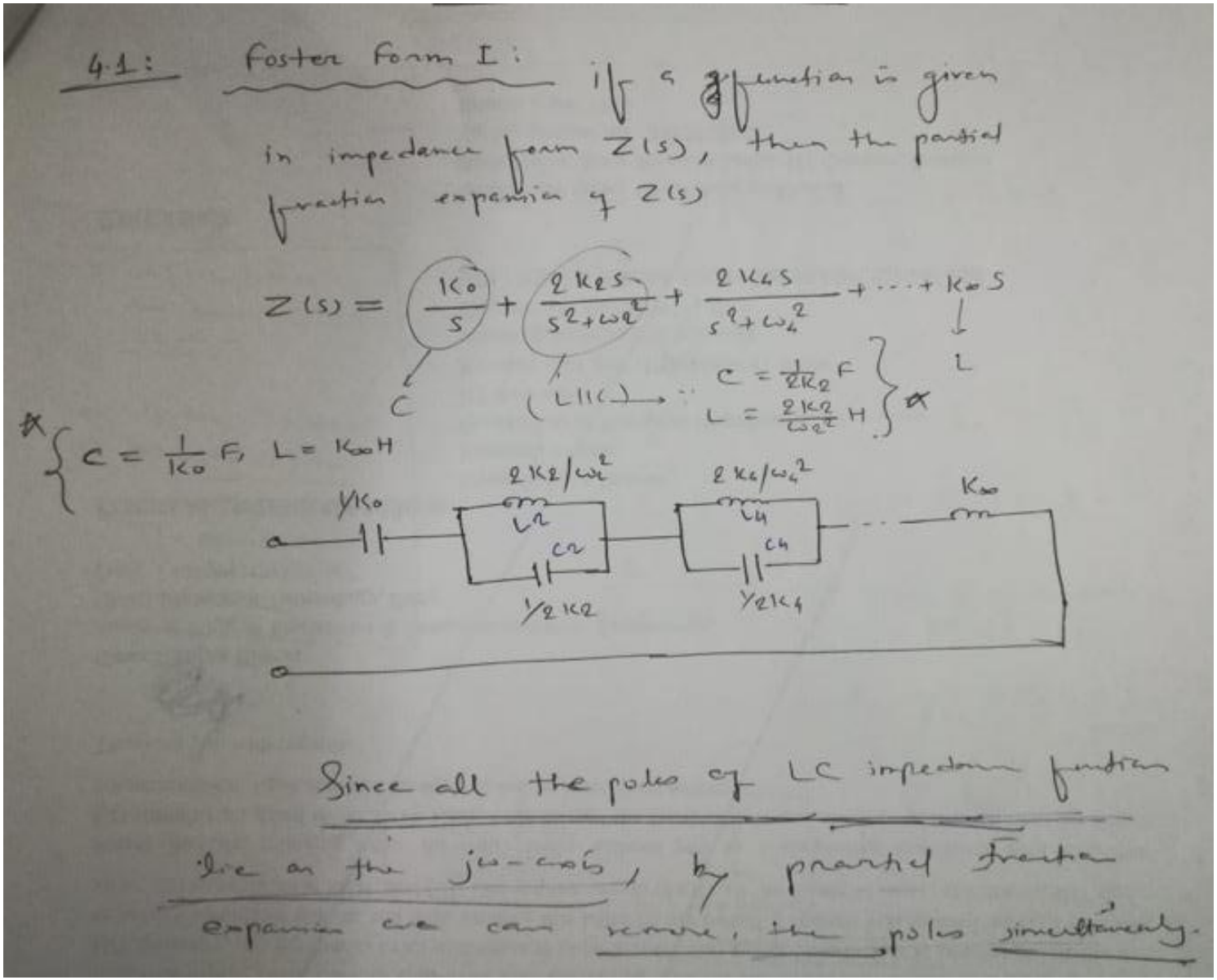
$$\downarrow$$

$$X(j\omega) = \frac{K_\omega(\omega_3^2-\omega^2)}{(\omega_2^2-\omega^2)(\omega_4^2-\omega^2)}$$

$$Z(s) = \frac{K_s(s^2+8)}{(s^2+3)(s^2+5)}$$

→ doesn't (X) LC immittance because the separation property doesn't hold good.

Foster Form - I



Foster Form – I: Practice Problem

Ex:

$$Z(s) = \frac{(s^2+3)(s^2+5)}{s(s^2+4)(s^2+6)}$$

Foster Form I (removing Z(s)):

$$Z(s) = \frac{(s^2+3)(s^2+5)}{s(s^2+4)(s^2+6)} = \frac{K_0}{s} + \frac{2K_2 s}{s^2+4} + \frac{2K_4 s}{s^2+6}$$

Now,

$$K_0 = [sZ(s)]_{s=0} = \left.\frac{(s^2+3)(s^2+5)}{(s^2+4)(s^2+6)}\right|_{s=0} = \frac{5}{8}$$

$$2K_2 = \left[(s^2+4)Z(s)\right]_{s^2=-4} = \left.\frac{s(s^2+3)(s^2+5)}{s^2(s^2+6)}\right|_{s^2=-4} = \frac{1}{8}s$$

$\therefore 2K_2 = \frac{1}{8}$

$$2K_4 s = \left[(s^2+6)Z(s)\right]_{s^2=-6} = \left.\frac{s(s^2+3)(s^2+5)}{s^2(s^2+4)}\right|_{s^2=-6} = \frac{1}{4}s$$

$\therefore 2K_4 = 1/4$

i.e.

$C_0 = \frac{8}{5}$ F

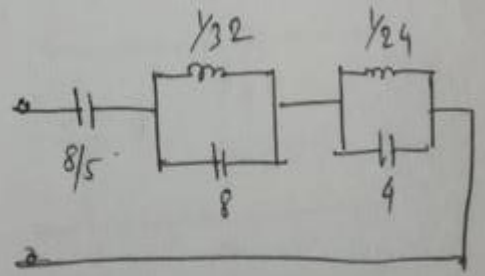
$C_2 = 8$ F

$C_4 = 4$ F

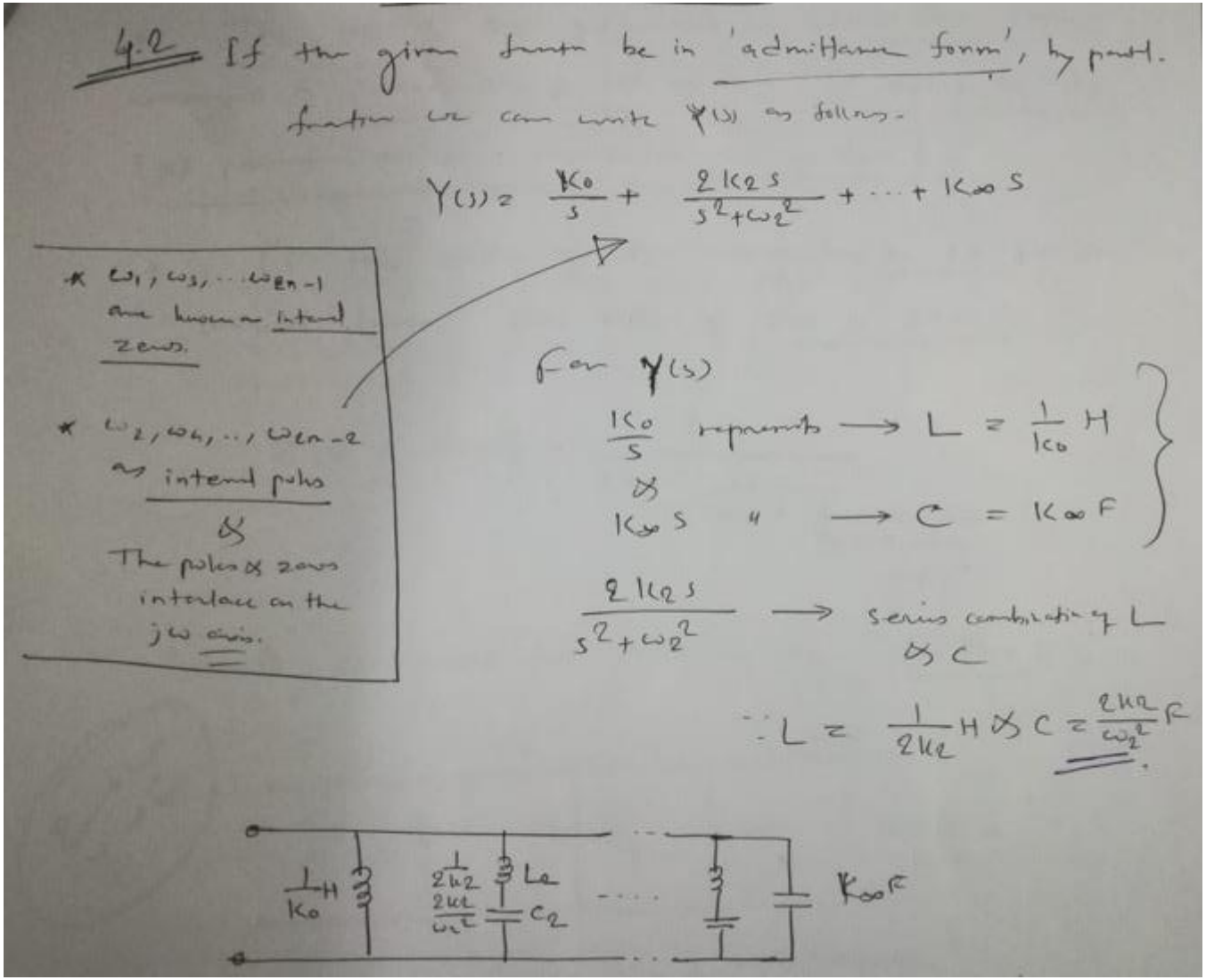
ans

$L_2 = \frac{2K_2}{\omega_2^2} = \frac{1}{8} \times \frac{1}{4} = \frac{1}{32}$ H

$L_4 = \frac{2K_4}{\omega_4^2} = \frac{1}{4} \times \frac{1}{6} = \frac{1}{24}$ H



Foster Form - II



Foster Form – II: Practice Problem

Foster Form II

Ex: $Y(s) = \frac{s(s^2+4)(s^2+6)}{(s^2+3)(s^2+5)}$ — (1)

$\therefore Y(s) = \frac{s^5+10s^3+24s}{s^4+8s^2+15}$

$s^4+8s^2+15 \;\big|\; s^5+10s^3+24s \;\big|\; s$

s^5+8s^3+15s

$2s^3+9s$

$Y(s) = s + \frac{2s^3+9s}{s^4+8s^2+15} = s + \frac{2s^3+9s}{(s^2+3)(s^2+5)}$

$= s + \frac{2k_2 s}{s^2+3} + \frac{2k_4 s}{s^2+5}$ — (2)

Now $2k_2 s = (s^2+3)Y(s)\big|_{s^2=-3}$

$\Rightarrow 2k_2 = \frac{s(s^2+4)(s^2+6)}{(s^2+5)}\Big|_{s^2=-3} = \frac{3}{2}s$

Again

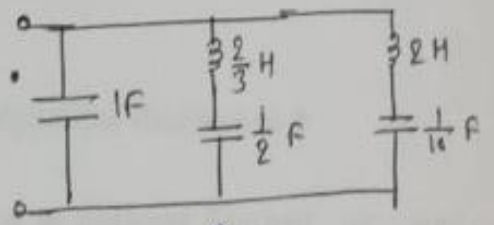
$2k_4 s = (s^2+5)Y(s)\big|_{s^2=-5}$

$= \frac{s(s^2+4)(s^2+6)}{(s^2+3)}\Big|_{s^2=-5}$

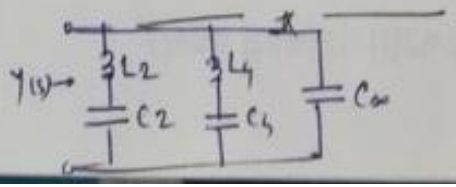
$\therefore 2k_4 s = \frac{s(-5+4)(-5+6)}{(-5+3)}$

$\therefore 2k_4 = \frac{1}{2}s$ & $2k_2 = \frac{3}{2}s$

i.e.



Or



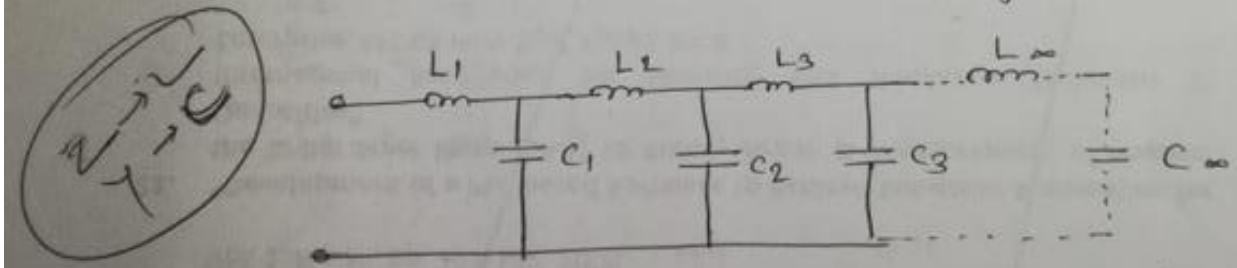
Cauer Form - I

* The $N(s)$ & $D(s)$ polynomials in Cauer form are arranged in descending powers of s. In every step the (X) pole at ∞ is removed in Cauer Form I.

* If the order of the numerator $N(s)$ be $2n$ for the original function, the order of $D(s)$ is $2n-1$.

$$\therefore Z(s) = Z_1(s) + \cfrac{1}{Y_1(s) + \cfrac{1}{Z_2(s) + \cfrac{1}{Y_2(s) + \cfrac{1}{Z_3(s) + \cdots}}}}$$

∴ A synthesized LC network using Cauer Form I is:



"Cauer Form I "LC" network"

Cauer Form - I

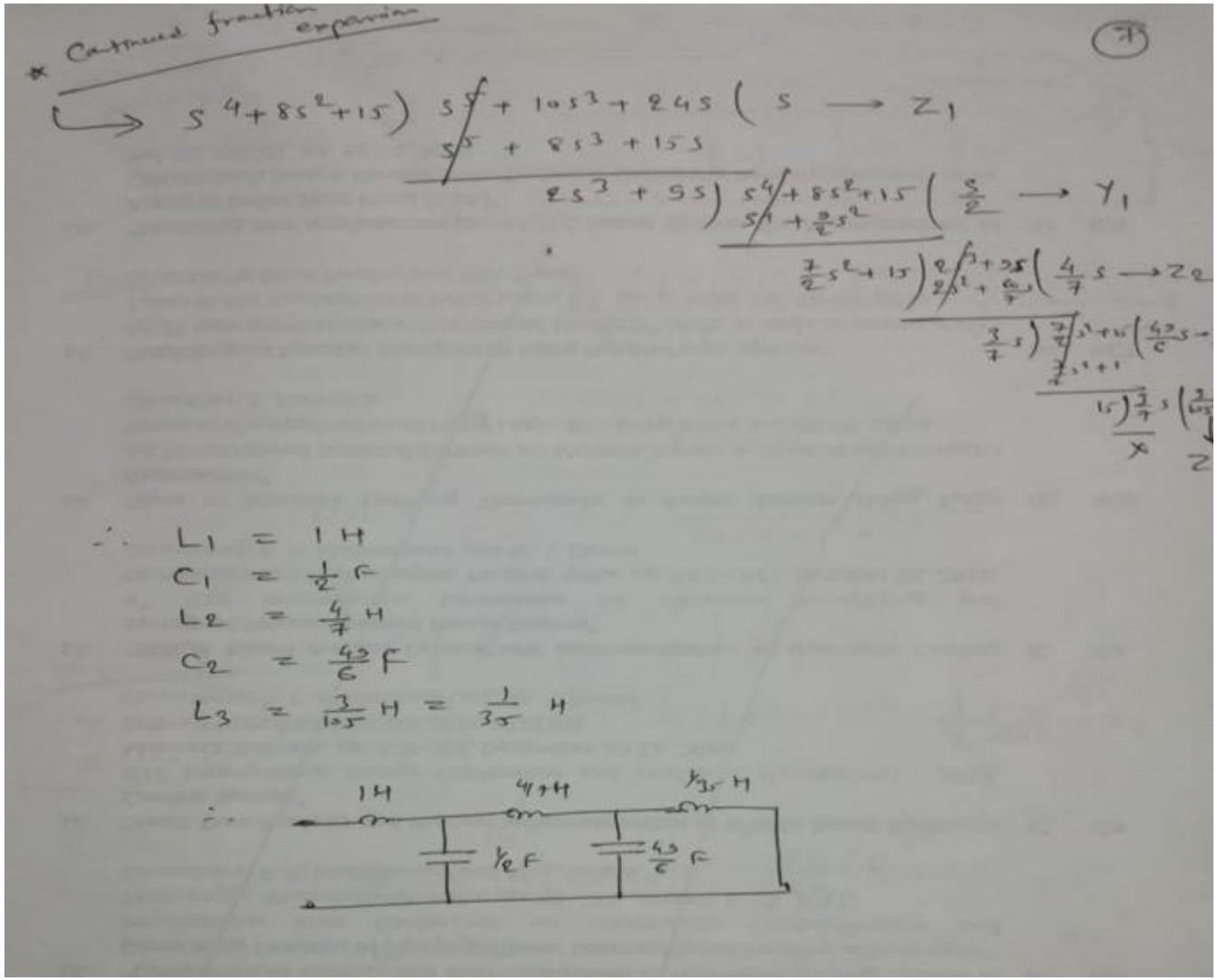
$$Z(s) = \frac{s(s^2+4)(s^2+6)}{(s^2+3)(s^2+5)}$$

since pole/zero of $Z(s)$ is $>$ $D(s)$ by 1, then pole at $s=\infty$ can be removed.

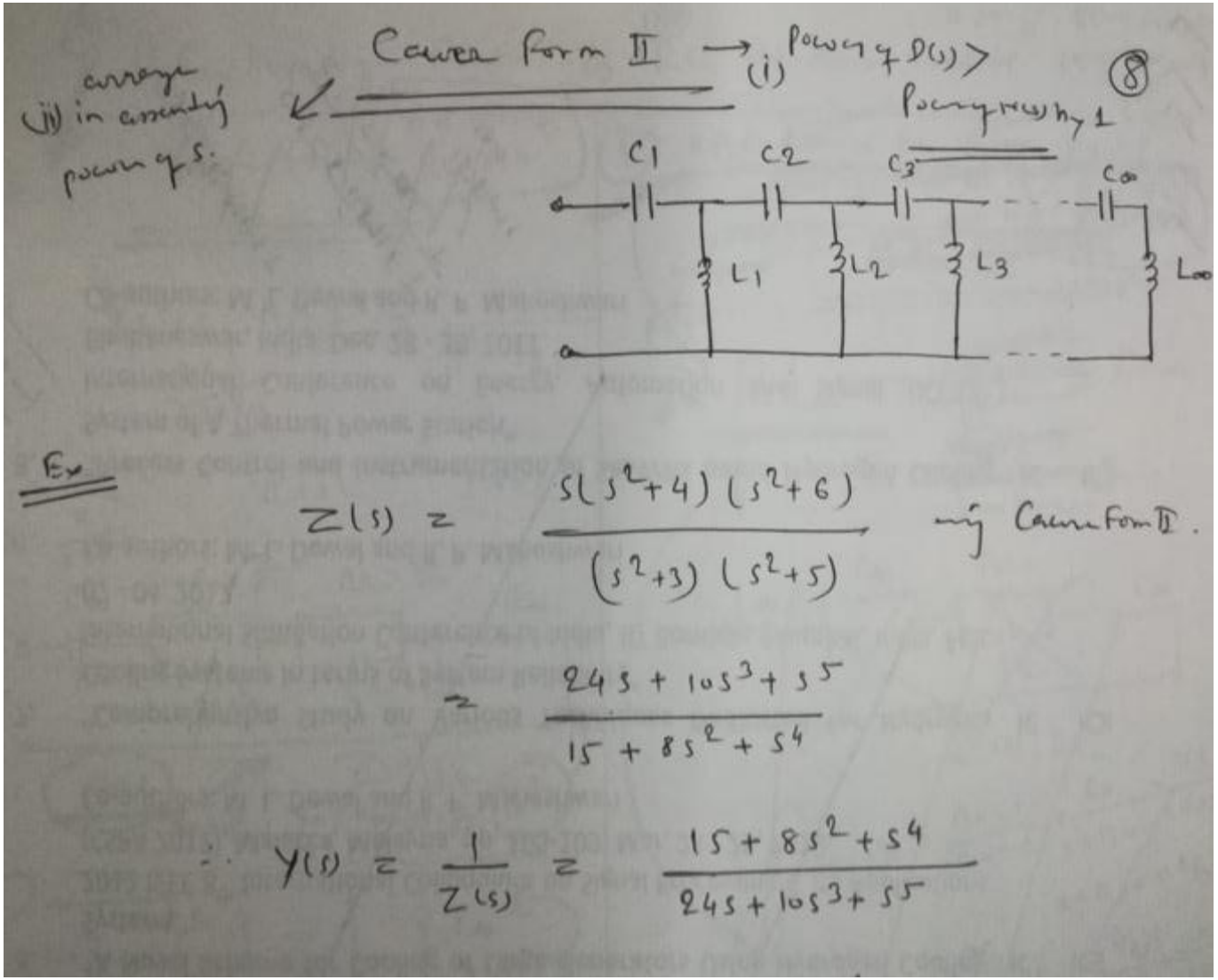
$$\therefore Z(s) = \frac{s^5+10s^3+24s}{s^4+8s^2+15}$$

Cauer Form - I

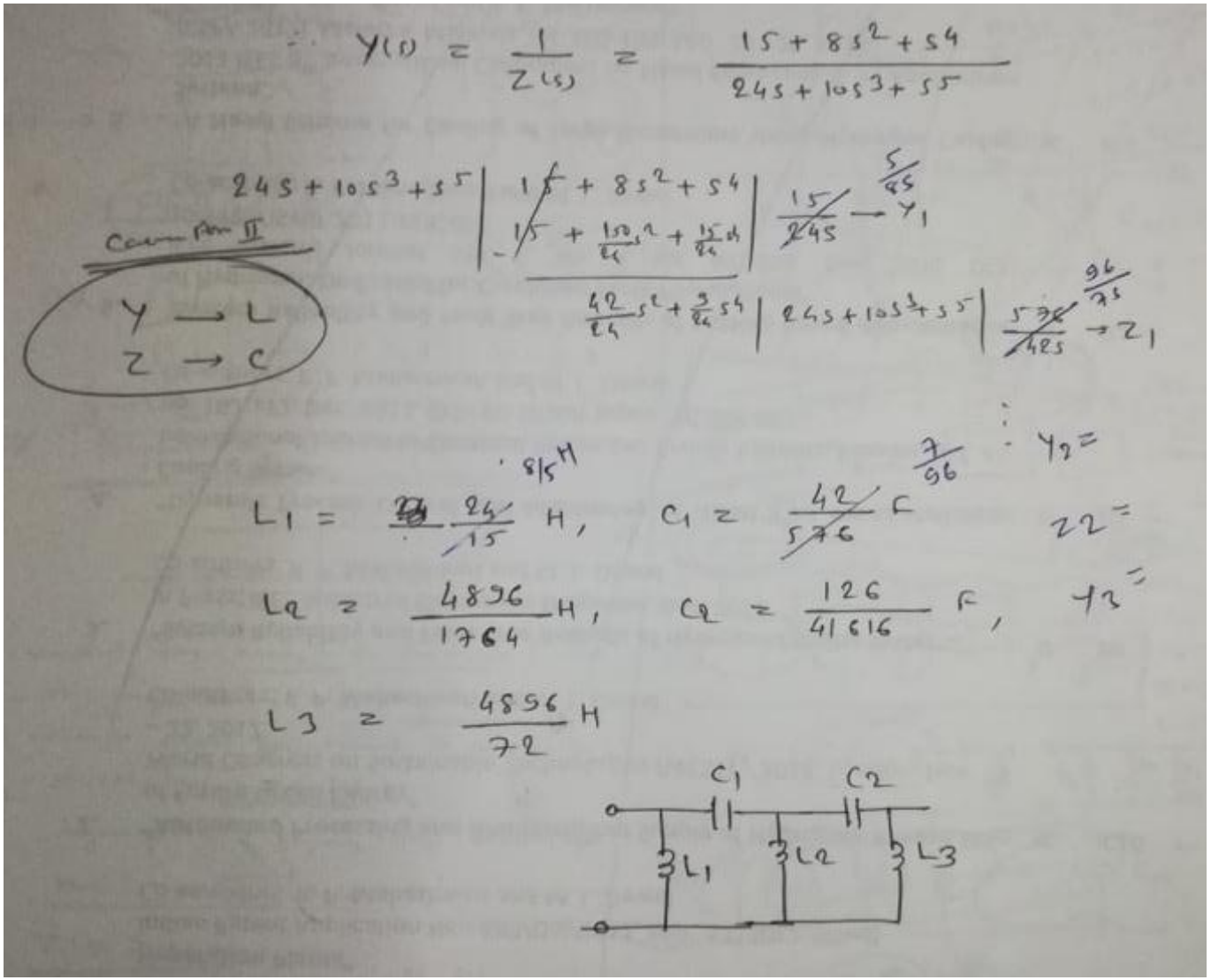
Continuous Fraction Expansion….



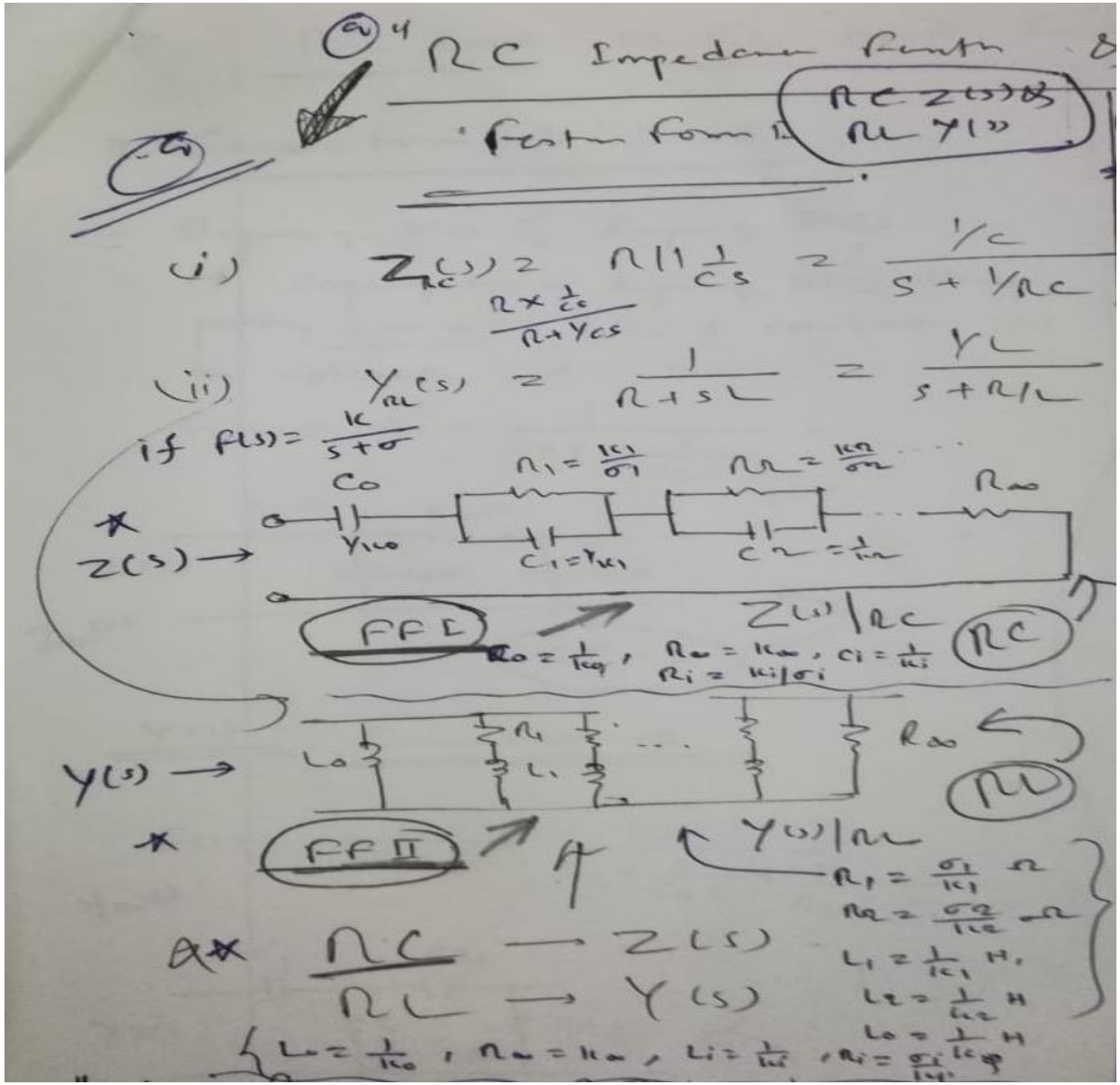
Cauer Form - II



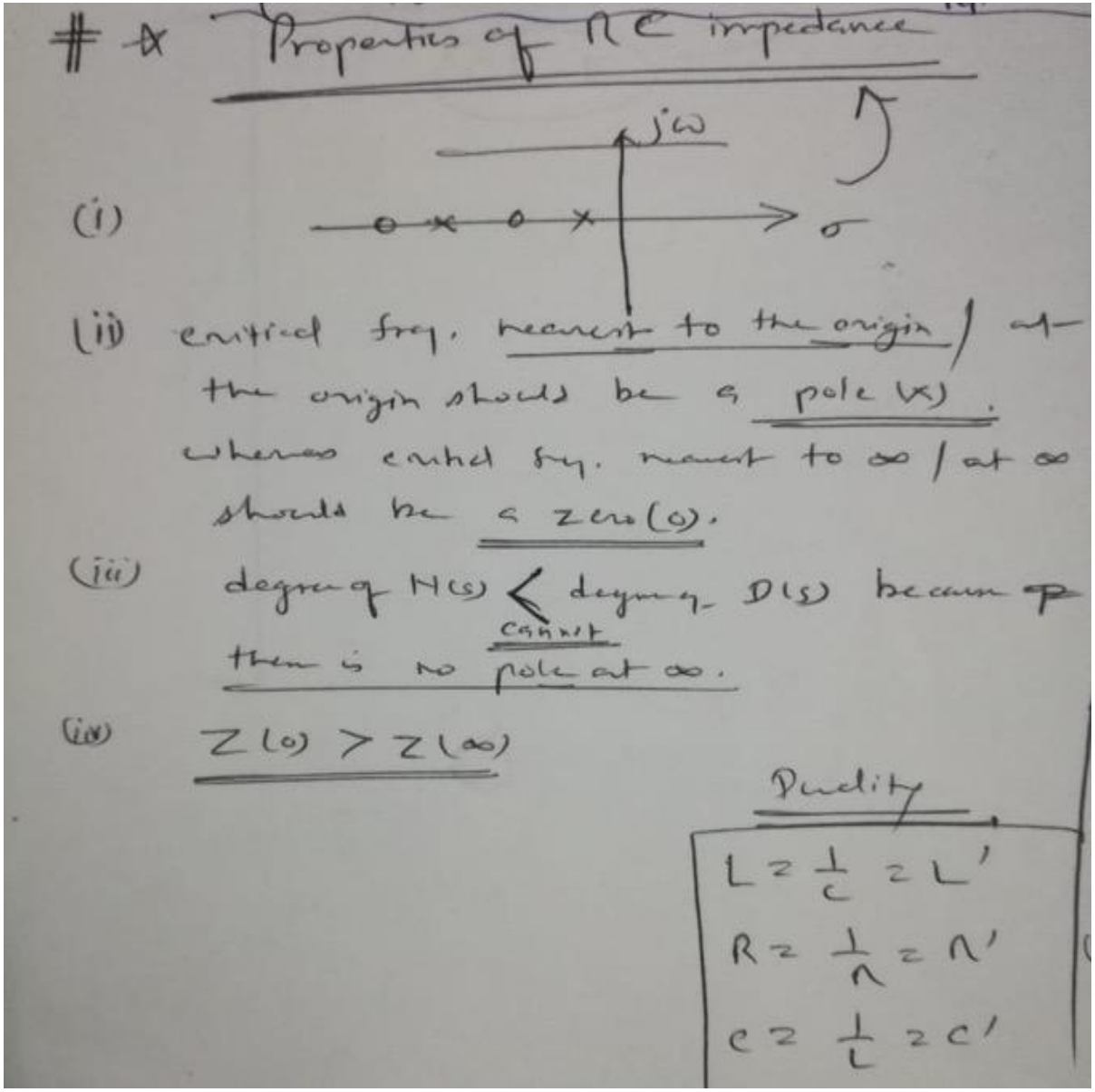
Cauer Form - II



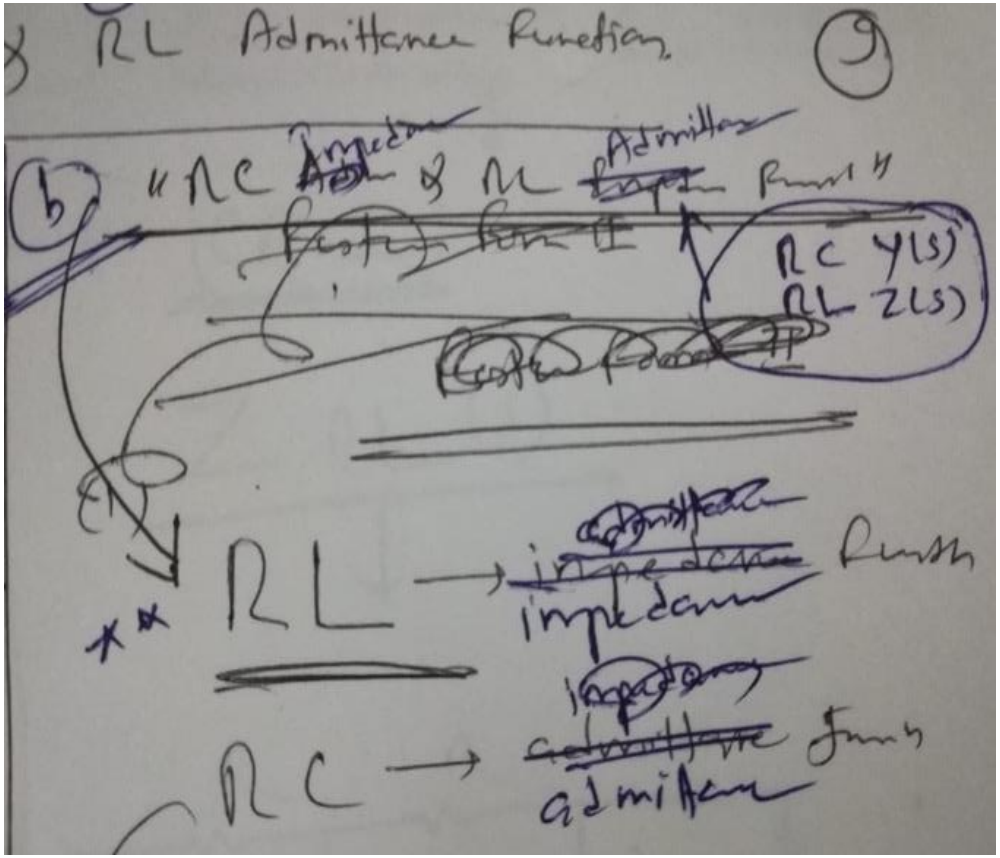
RC Impedance Function



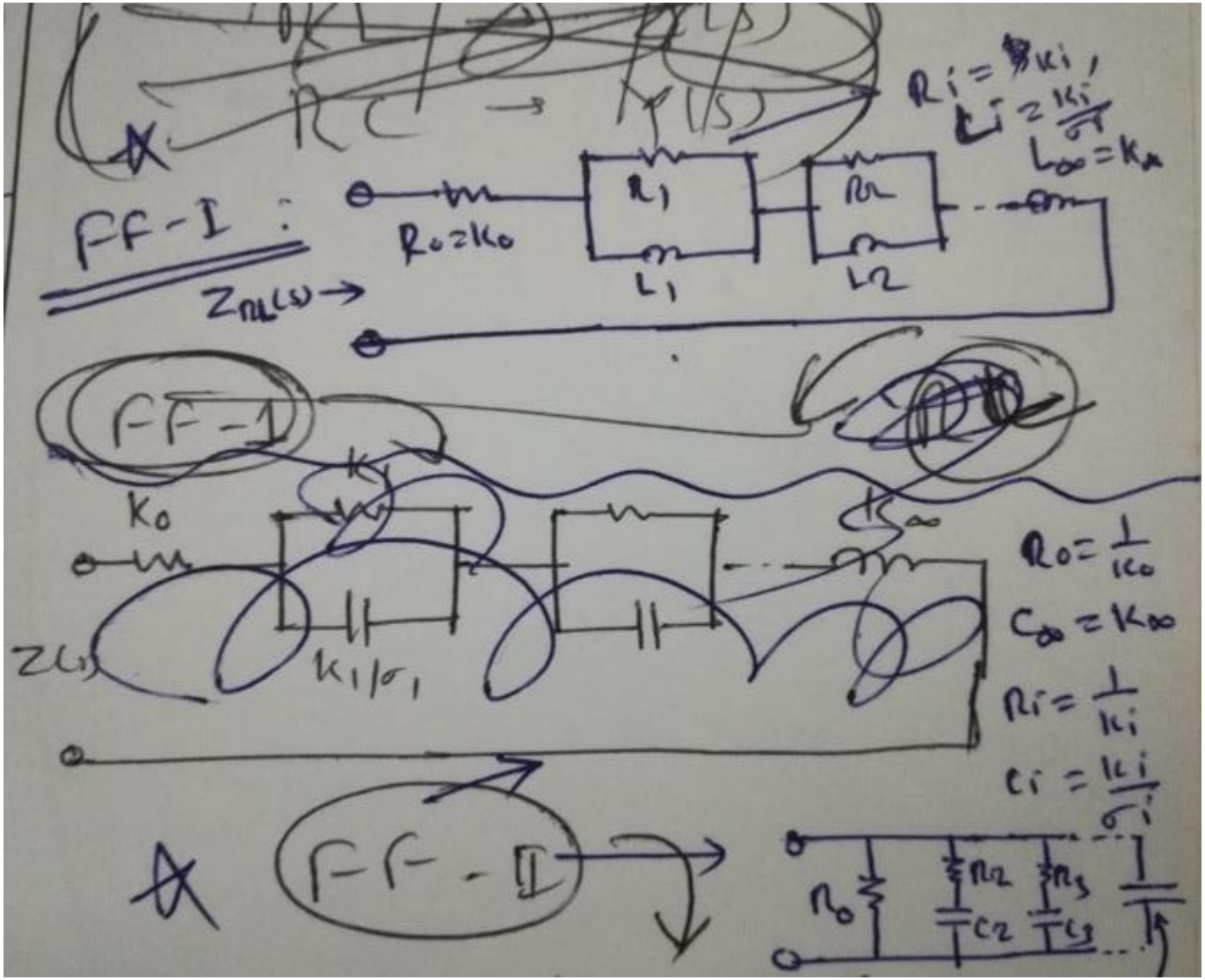
Properties of RC Impedance



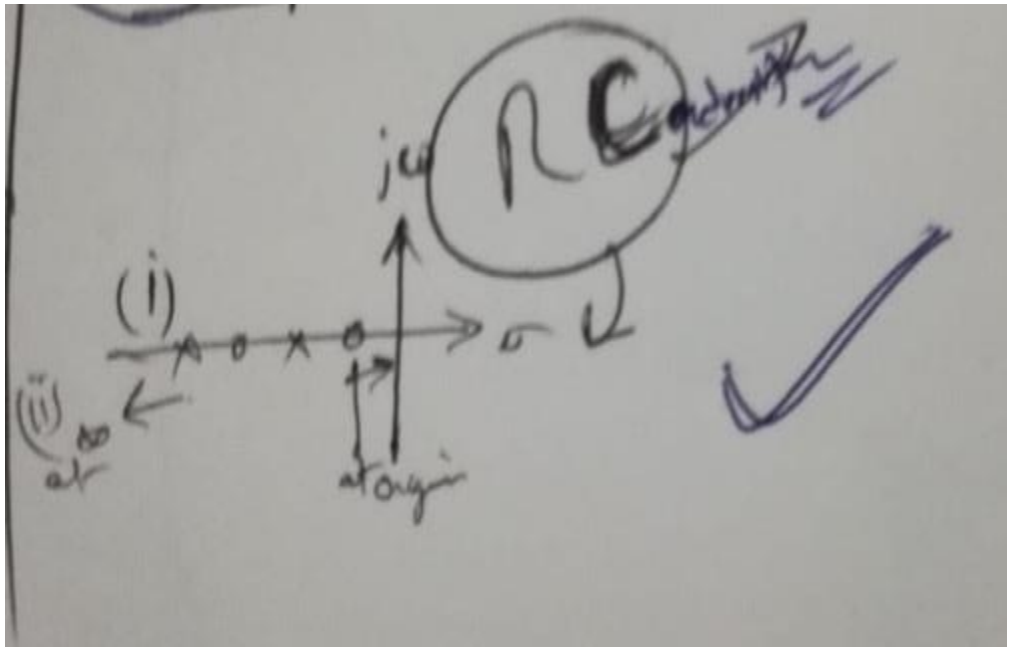
RL Admittance Function



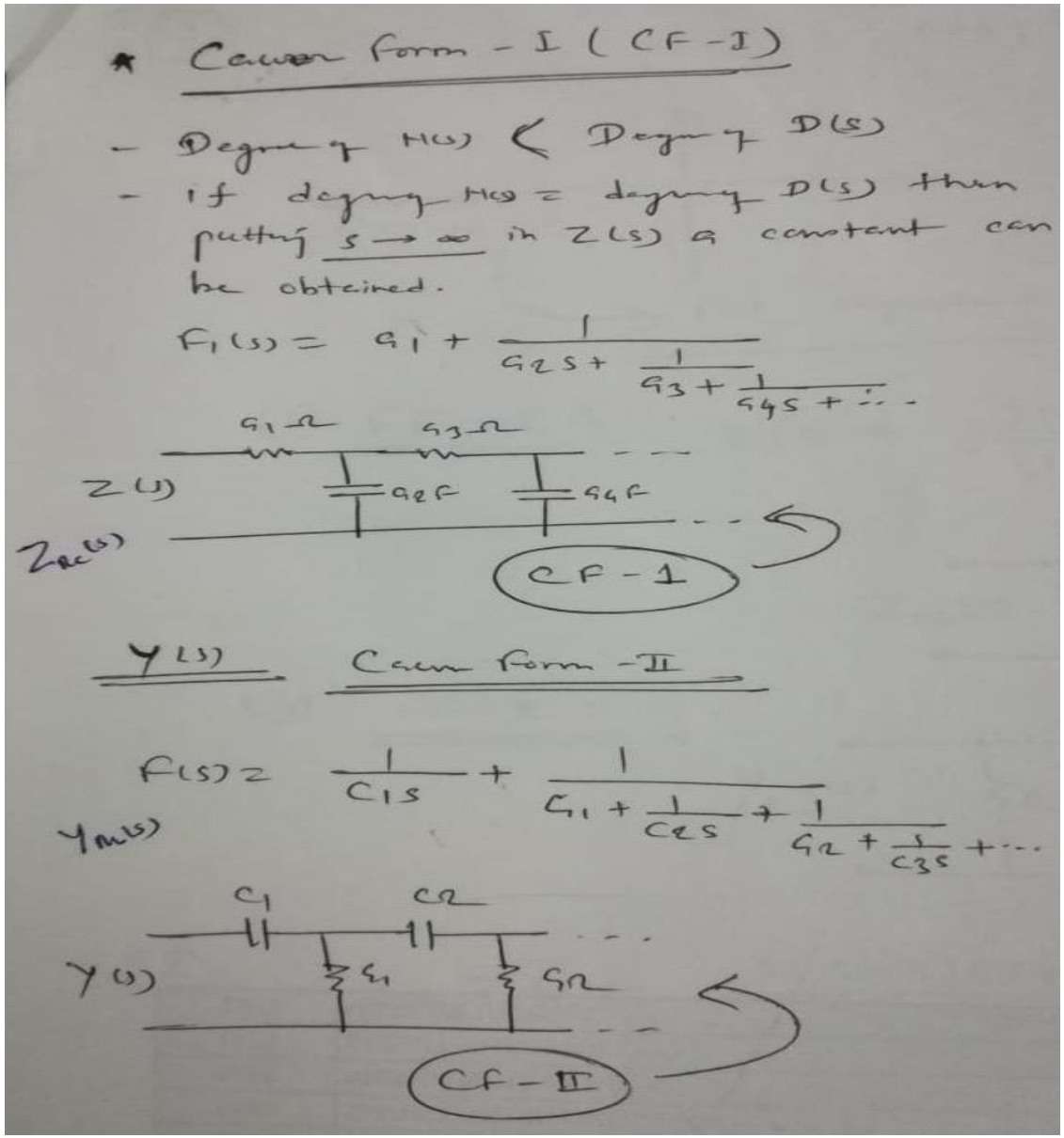
RL Admittance Function: FF-I and FF-II



RL Admittance Function: FF-I and FF-II

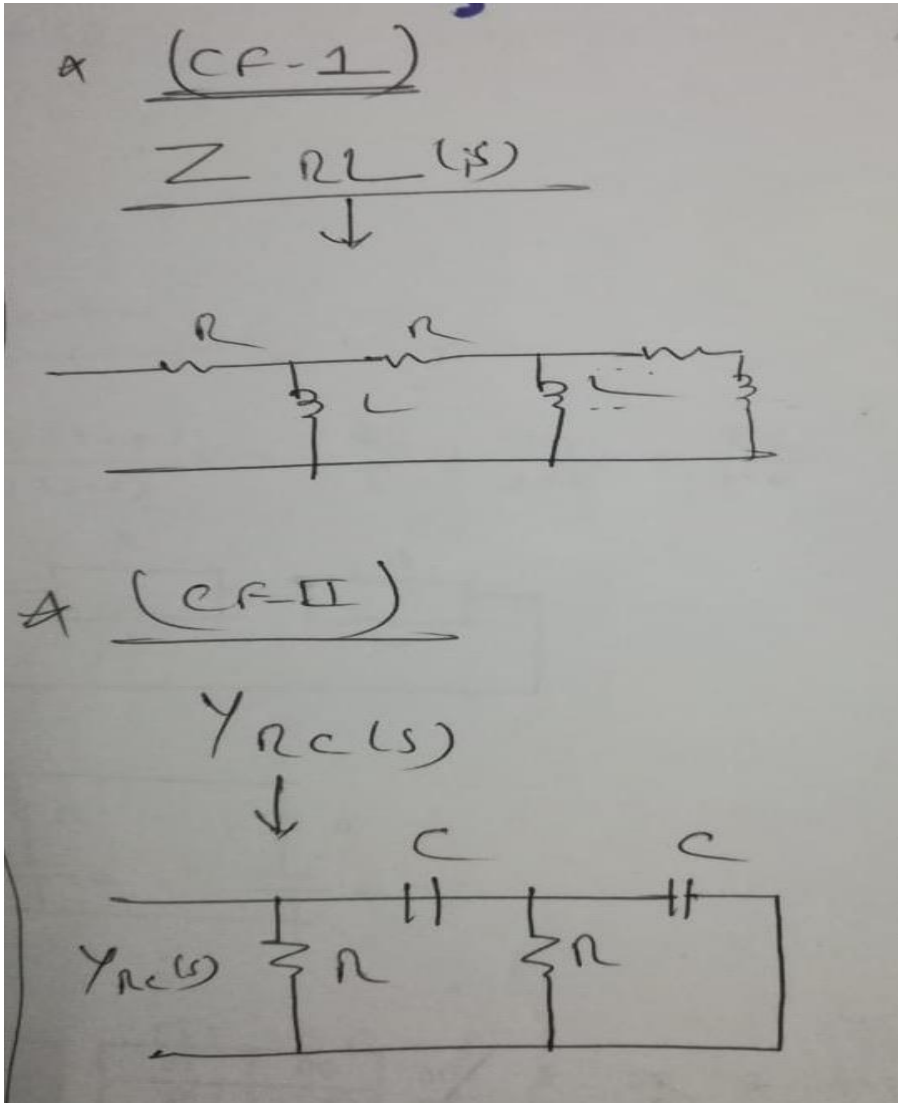


RC Impedance & RL Admittance Functions: CF-I and CF-II



RC Impedance & RL Admittance Functions:

CF-I and CF-II



Thank you