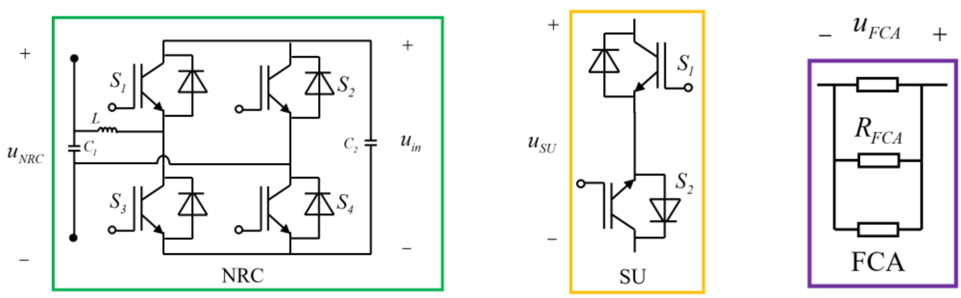
ภาคผนวก ก

ระบบ Negative Resistance Converter Traction Power System

ก.1 โหมดการทำงาน Negative Resistance Converter

Negative resistance converter เป็นอุปกรณ์ที่ใช้วงจร DC–DC full-bridge converter มีค่าความต้านทานเอาต์พุตเทียบเท่าค่าเป็นลบและค่าแรงดันเอาต์พุตสามารถยืดหยุ่นได้ ดังรูปที่ ก.1(ก), SU เป็นสวิตซ์แบบสองทิศทาง ใช้ IGBTs ต่อกันสองตัวแบบอนุกรมย้อนกลับ (reverse series) ดังรูปที่ ก.1(ข) และ FCA เป็นสายเคเบิลที่ต่อแบบขนาน ดังรูปที่ ก.1(ค) NRC และ SU เป็นอุปกรณ์ที่มีพลังงานการไหลได้แบบสองทิศทาง

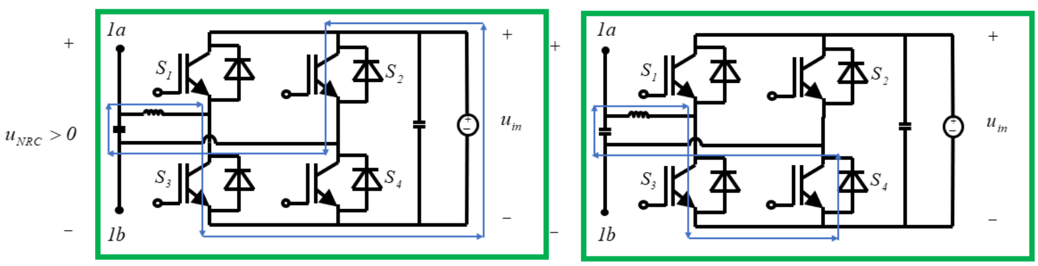


(ก) (ข) (ค)

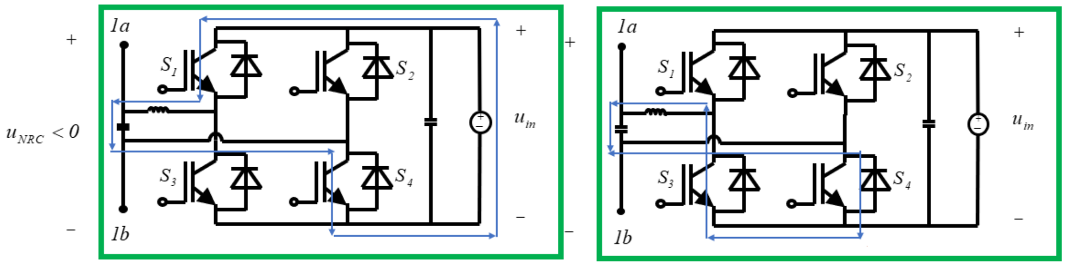
รูปที่ ก.1 อุปกรณ์ของระบบ NEG-TPS (ก) NRC. (ข) SU. (ค) FCA.

โหมดการทำงานของ NRC

โหมดการทำงานของ NRC จะถูกกำหนดโดยค่าแรงดันไฟฟ้าตกคร่อม FCA ในลูปความต้านทานเป็นศูนย์ แรงดันไฟฟ้าตกคร่อม FCA จะมีค่าแตกต่างกันเมื่อรถไฟทำงานอยู่ในสภาวะที่ต่างกัน เมื่อแรงดันขาออก (u_{NRC}) ของ NRC จะมีค่าเป็นบวกสำหรับชดเชยค่าแรงดันของ FCA ดังรูปที่ ก.2(ก) แสดงโหมดการทำงานของ NRC การควบคุมพัลส์ (PWM) จะถูกนำมาใช้กับ S_2 และ S_3 ที่ถูกเปิดการใช้งาน, S_1 และ S_4 ถูกปิดการใช้งาน และเมื่อ u_{NRC} จะมีค่าเป็นลบสำหรับชดเชยค่าแรงดันของ FCA ดังรูปที่ ก.2(ข) การควบคุม PWM จะถูกนำมาใช้กับ S_1 และ S_4 ที่ถูกเปิดการใช้งาน, S_2 และ S_3 ถูกปิดการใช้งานตลอดเวลา ทั้งในโหมด 1 และ 2 ของ NRC จะเทียบเท่าการแปลงแรงดันให้ลดลง (buck converter) เนื่องจาก u_{NRC} สามารถทำงานได้ภายใต้เงื่อนไขรถไฟหลายสภาวะการทำงาน



(ก)

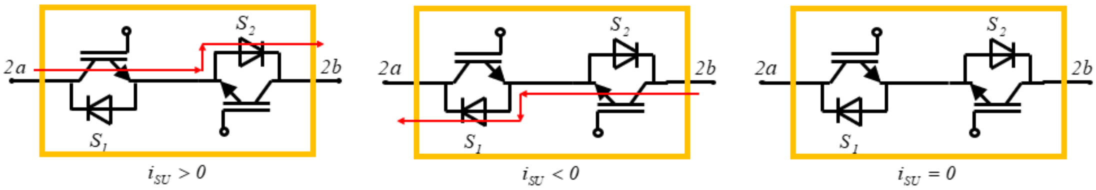


(ข)

รูปที่ ก.2 โหมดการทำงานของ NRC (ก) โหมดการทำงานที่ 1 (ข) โหมดการทำงานที่ 2

โหมดการทำงานของ SU

โหมดการทำงานของ SU จะถูกกำหนดโดยตำแหน่งของรถไฟและทิศทางการไหลของกระแสราง ทิศทางของกระแสรางจะแตกต่างกันเมื่อรถไฟทำงานในสภาวะที่ต่างกัน ปลายขั้วของ SU ทั้งสองจะถูกเปิดใช้งานเมื่อรถไฟอยู่ในตำแหน่งตรงกลางของ SU ทั้งสองและ SU ส่วนอื่น ๆ ที่ไม่ใช่ส่วนของรางที่ตำแหน่งรถไฟก็จะถูกปิดการใช้งาน ซึ่งโหมดการทำงานของ SU ดังรูปที่ 3.28 โหมดการทำงานของ SU ในโหมดการทำงานที่ 1 เมื่อกระแสรางไหลจาก 2a ไปยัง 2b, S_1 จะเปิดการใช้งานและ S_2 จะไม่เปิดใช้งาน ดังรูปที่ ก.3(ก) และในโหมดการทำงานที่ 2 กระแสรางไหลจาก 2b ไปยัง 2a, S_1 จะถูกปิดการใช้งานและ S_2 จะถูกเปิดการใช้งานขึ้น ดังรูปที่ ก.3(ข) ซึ่ง SU สามารถทำงานภายใต้เงื่อนไขรถไฟหลายสภาวะการทำงานที่มีกระแสรางไหลไปในทิศทางที่แตกต่างกัน และในโหมดการทำงานที่ 3 ทั้ง S_1 และ S_2 จะถูกปิดการใช้งานและกระแสรางไม่สามารถไหลผ่าน SU ได้ดังรูปที่ ก.3 (ค)



(ก) (ข) (ค)

รูปที่ ก.3 โหมดการทำงานของ SU

(ก) โหมดการทำงานที่ 1 (ข) โหมดการทำงานที่ 2 (ค) โหมดการทำงานที่ 3

ภาคผนวก ข

ผลการจำลองกรณีศึกษาที่ 2 (รถไฟฟ้าขบวนเดียว MRT สายสีม่วงเหนือ)

ระบบติดตั้งตัวนำย้อนกลับ

ข.1 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ

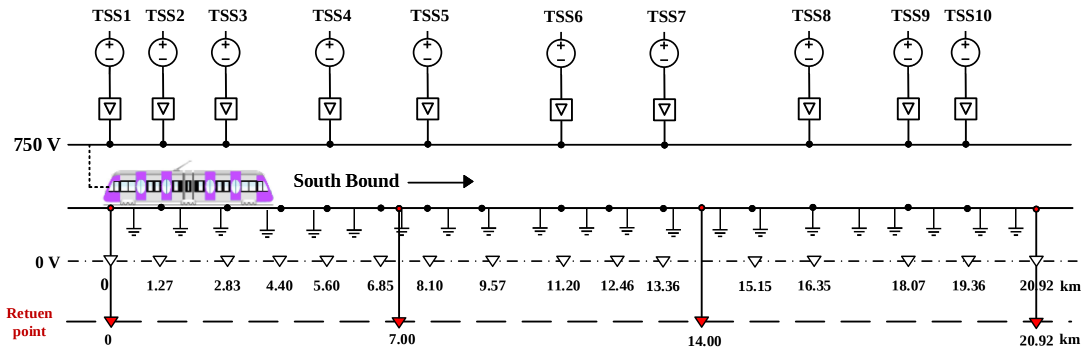
ข1.1 ผลการจำลองการติดตั้งจุดเชื่อมต่อ 3 จุดเชื่อมต่อ

ตารางที่ ข.1 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 3 จุดเชื่อมต่อ

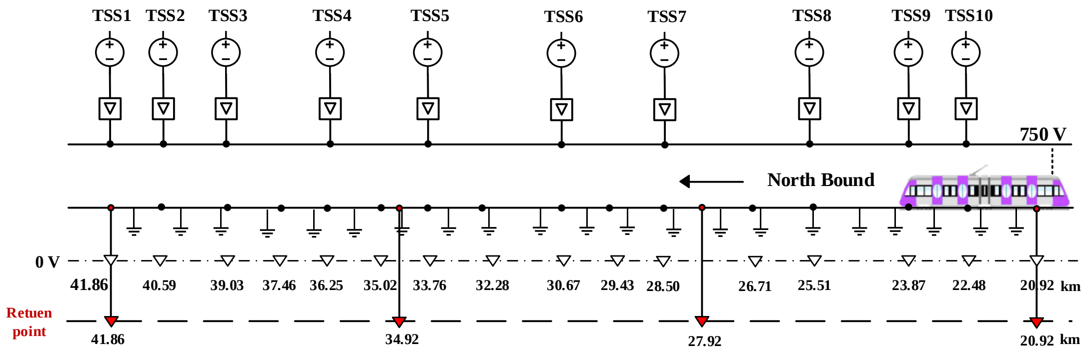
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.508	729.372	10.891	-0.973	0.050	-0.045
TSS2	2.287	731.234	12.141	-0.973	0.050	-0.045
TSS3	2.459	729.781	13.508	-2.586	0.050	-0.044
TSS4	2.555	728.969	14.094	-3.040	0.047	-0.043
TSS5	2.575	728.803	13.605	-1.401	0.039	-0.041
TSS6	2.507	729.375	11.980	-0.976	0.031	-0.038
TSS7	2.547	729.041	13.949	-4.605	0.025	-0.036
TSS8	2.460	729.773	13.541	-5.789	0.022	-0.032
TSS9	2.308	731.057	12.509	-7.184	0.019	-0.033
TSS10	2.430	730.027	12.144	-2.554	0.016	-0.033
North Bound						
TSS10	2.400	730.281	12.217	-2.065	0.011	-0.032
TSS9	2.317	730.984	12.584	-6.861	0.013	-0.031
TSS8	2.484	729.568	13.679	-5.366	0.013	-0.028
TSS7	2.535	729.140	13.798	-2.895	0.012	-0.018
TSS6	2.495	729.479	10.887	-0.964	0.010	-0.011
TSS5	2.572	728.828	13.952	-2.026	0.013	-0.009
TSS4	2.559	728.939	14.108	-2.306	0.016	-0.011
TSS3	2.435	729.984	13.312	-1.098	0.018	-0.012
TSS2	2.280	731.294	11.845	-0.971	0.018	-0.013
TSS1	0.890	742.811	3.138	-0.949	0.018	-0.013

ข1.2 แบบจำลองและผลการจำลองการติดตั้งจุดเชื่อมต่อ 4 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



(ก)



(ข)

รูปที่ ข.1 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 4 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ข.2 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 4 จุดเชื่อมต่อ

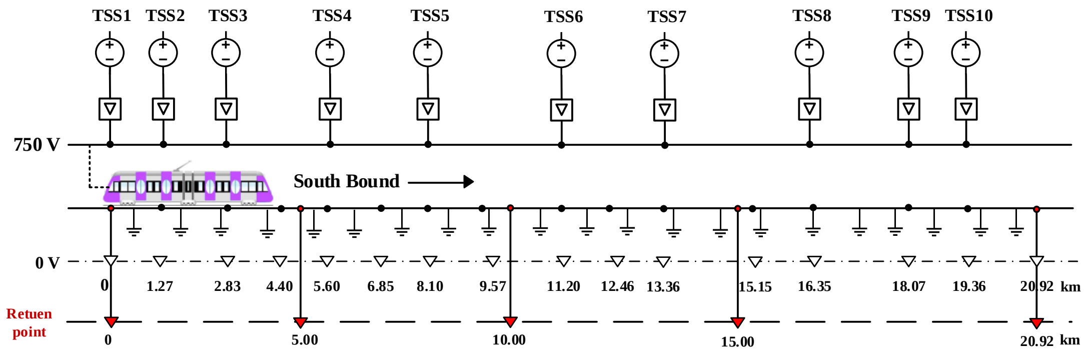
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.494	729.486	10.705	-0.867	0.051	-0.043
TSS2	2.287	731.236	12.151	-1.328	0.051	-0.043
TSS3	2.459	729.782	13.477	-3.566	0.049	-0.043
TSS4	2.532	729.161	12.745	-1.823	0.042	-0.041
TSS5	2.552	728.997	12.734	-0.965	0.035	-0.039
TSS6	2.540	729.094	13.868	-3.644	0.029	-0.037
TSS7	2.487	729.547	11.374	-0.896	0.024	-0.035
TSS8	2.455	729.816	13.082	-3.402	0.019	-0.031
TSS9	2.308	731.057	12.501	-6.009	0.018	-0.029
TSS10	2.422	730.093	12.142	-2.540	0.016	-0.027
North Bound						
TSS10	2.394	730.331	12.236	-2.278	0.011	-0.022
TSS9	2.317	730.985	12.527	-5.266	0.013	-0.020
TSS8	2.460	729.773	12.360	-2.091	0.011	-0.017
TSS7	2.514	729.320	12.761	-2.357	0.010	-0.012
TSS6	2.553	728.984	13.988	-5.514	0.013	-0.013
TSS5	2.543	729.076	12.447	-1.203	0.012	-0.010
TSS4	2.539	729.103	12.928	-1.064	0.013	-0.010
TSS3	2.435	729.984	13.292	-3.234	0.018	-0.011
TSS2	2.279	731.299	11.863	-1.127	0.018	-0.012
TSS1	0.884	742.863	3.053	-0.846	0.018	-0.012

ตารางที่ ข.3 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัว 4 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.82	PP15	21.41
PP02	20.34	PP14	21.10
PP03	28.54	PP13	20.51
PP04	61.51	PP12	66.49
PP05	24.62	PP11	26.56
PP06	41.87	PP10	49.22
PP07	28.55	PP09	24.33
PP08	70.57	**PP08**	**70.93**
PP09	26.26	PP07	27.94
PP10	47.63	PP06	56.55
PP11	19.25	PP05	28.69
PP12	59.98	PP04	62.27
PP13	23.73	PP03	20.94
PP14	23.61	PP02	20.92
PP15	27.63	PP01	1.02
PP16	59.35	**สูงสุด**	**70.93**
		เฉลี่ย	**35.55**

ข1.3 แบบจำลองการติดตั้งจุดเชื่อมต่อ 5 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



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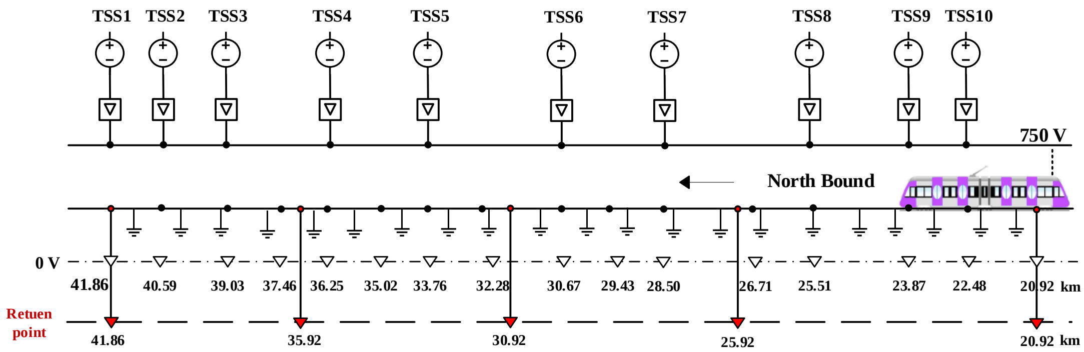


(ข)

รูปที่ ข.2 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 5 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ข.4 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 5 จุดเชื่อมต่อ

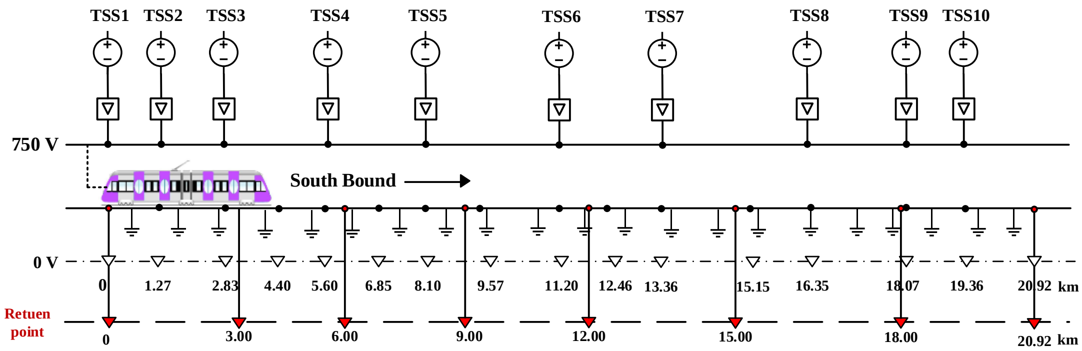
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.479	729.617	10.520	-0.823	0.051	-0.043
TSS2	2.287	731.236	12.107	-1.371	0.051	-0.043
TSS3	2.451	729.854	12.955	-1.769	0.047	-0.043
TSS4	2.490	729.519	11.735	-0.827	0.039	-0.041
TSS5	2.561	728.923	13.222	-2.493	0.033	-0.040
TSS6	2.503	729.410	12.458	-1.756	0.025	-0.037
TSS7	2.523	729.242	12.853	-2.966	0.022	-0.035
TSS8	2.432	730.014	12.248	-2.174	0.016	-0.032
TSS9	2.308	731.059	12.443	-5.446	0.018	-0.030
TSS10	2.418	730.127	12.130	-2.504	0.016	-0.028
North Bound						
TSS10	2.391	730.357	12.264	-2.063	0.011	-0.023
TSS9	2.316	730.990	12.422	-3.960	0.013	-0.021
TSS8	2.392	730.349	10.512	-0.860	0.011	-0.018
TSS7	2.532	729.162	13.584	-2.124	0.011	-0.012
TSS6	2.442	729.923	10.335	-0.865	0.010	-0.007
TSS5	2.569	728.854	13.623	-1.129	0.013	-0.008
TSS4	2.480	729.609	11.246	-0.813	0.011	-0.010
TSS3	2.435	729.987	13.243	-2.226	0.018	-0.011
TSS2	2.276	731.325	11.966	-1.387	0.018	-0.011
TSS1	0.893	742.790	3.389	-0.810	0.019	-0.012

ตารางที่ ข.5 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัวนำย้อนกลับ 5 จุดเชื่อมต่อ

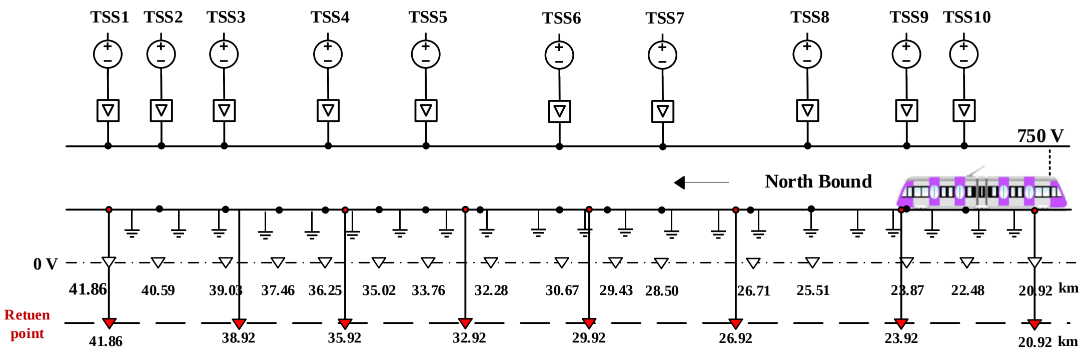
South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.83	PP15	21.34
PP02	20.34	PP14	20.81
PP03	22.09	PP13	16.03
PP04	51.92	PP12	60.98
PP05	27.20	PP11	26.19
PP06	56.16	PP10	48.45
PP07	26.73	PP09	17.33
PP08	53.43	**PP08**	**67.47**
PP09	25.89	PP07	26.77
PP10	47.94	PP06	52.09
PP11	21.60	PP05	27.19
PP12	46.47	PP04	61.53
PP13	23.33	PP03	30.00
PP14	23.37	PP02	19.68
PP15	25.48	PP01	1.01
PP16	47.21	**สูงสุด**	**67.47**
		เฉลี่ย	**33.41**

ข1.4 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 8 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



(ก)



(ข)

รูปที่ ข.3 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 8 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ข.6 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 8 จุดเชื่อมต่อ

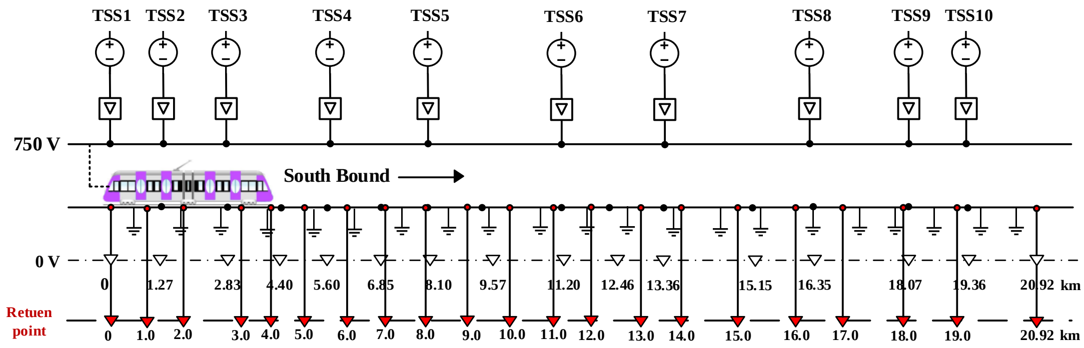
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.443	729.918	10.285	-0.777	0.050	-0.041
TSS2	2.286	731.240	12.094	-1.170	0.050	-0.041
TSS3	2.293	731.187	9.498	-0.777	0.046	-0.040
TSS4	2.432	730.010	10.780	-0.777	0.039	-0.039
TSS5	2.503	729.407	11.936	-0.802	0.032	-0.038
TSS6	2.481	729.599	11.793	-0.803	0.025	-0.035
TSS7	2.508	729.367	12.457	-0.801	0.020	-0.033
TSS8	2.422	730.094	12.371	-0.799	0.018	-0.030
TSS9	2.176	732.165	9.072	-0.798	0.015	-0.028
TSS10	2.407	730.219	12.301	-0.797	0.015	-0.027
North Bound						
TSS10	2.383	730.429	12.254	-0.795	0.013	-0.022
TSS9	2.169	732.230	8.659	-0.794	0.011	-0.020
TSS8	2.441	729.934	12.356	-0.793	0.011	-0.017
TSS7	2.499	729.444	12.404	-0.792	0.010	-0.011
TSS6	2.500	729.439	12.050	-0.791	0.010	-0.006
TSS5	2.506	729.382	12.130	-0.790	0.011	-0.008
TSS4	2.450	729.858	11.174	-0.790	0.012	-0.010
TSS3	2.290	731.205	9.881	-0.789	0.014	-0.011
TSS2	2.273	731.350	11.708	-0.855	0.018	-0.011
TSS1	0.859	743.062	2.415	-0.789	0.018	-0.012

ตารางที่ ข.7 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีย่อยไฟฟ้าของระบบติดตั้งตัวนำย้อนกลับ 8 จุดเชื่อมต่อ

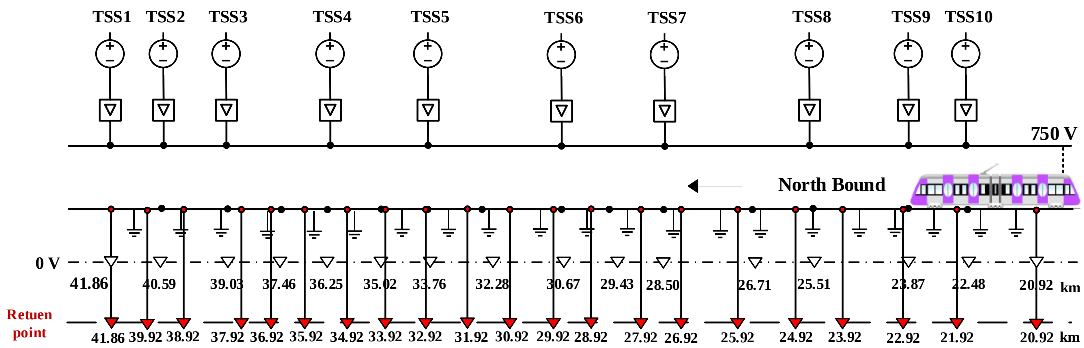
South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.84	PP15	20.88
PP02	20.16	PP14	17.92
PP03	24.95	PP13	18.61
PP04	59.33	PP12	42.41
PP05	20.85	PP11	23.63
PP06	51.58	PP10	39.88
PP07	21.91	PP09	22.38
PP08	56.69	PP08	56.38
PP09	20.04	PP07	26.32
PP10	39.34	PP06	51.70
PP11	21.35	PP05	27.13
PP12	42.22	**PP04**	**60.35**
PP13	23.05	PP03	28.32
PP14	21.81	PP02	19.77
PP15	25.29	PP01	0.98
PP16	41.79	**สูงสุด**	**60.35**
		เฉลี่ย	**31.19**

ข1.5 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 21 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



(ก)



(ข)

รูปที่ ข.4 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวนำย้อนกลับ 21 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ข.8 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 21 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.402	730.267	10.040	-0.036	0.043	-0.036
TSS2	2.141	732.459	9.625	-0.036	0.043	-0.036
TSS3	2.270	731.378	9.466	-0.036	0.040	-0.036
TSS4	2.402	730.268	10.455	-0.035	0.033	-0.035
TSS5	2.426	730.062	10.388	-0.034	0.028	-0.034
TSS6	2.395	730.322	10.438	-0.031	0.023	-0.031
TSS7	2.404	730.246	10.615	-0.030	0.020	-0.030
TSS8	2.310	731.040	10.292	-0.027	0.016	-0.027
TSS9	2.123	732.609	8.743	-0.025	0.014	-0.025
TSS10	2.317	730.978	10.713	-0.024	0.014	-0.024
North Bound						
TSS10	2.265	731.423	10.068	-0.020	0.011	-0.020
TSS9	2.098	732.824	8.292	-0.018	0.010	-0.018
TSS8	2.325	730.911	10.235	-0.015	0.010	-0.015
TSS7	2.391	730.354	10.460	-0.010	0.009	-0.010
TSS6	2.391	730.360	10.147	-0.006	0.009	-0.006
TSS5	2.401	730.277	9.909	-0.007	0.010	-0.007
TSS4	2.412	730.179	10.602	-0.008	0.012	-0.008
TSS3	2.275	731.334	9.788	-0.009	0.013	-0.009
TSS2	2.131	732.549	9.405	-0.010	0.015	-0.010
TSS1	0.932	742.470	3.256	-0.010	0.016	-0.010

ตารางที่ ข.9 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัวนำย้อนกลับ 21 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.12	PP15	22.74
PP02	17.09	PP14	17.28
PP03	22.46	PP13	15.59
PP04	42.45	PP12	39.95
PP05	19.71	PP11	17.89
PP06	34.14	PP10	36.72
PP07	21.66	PP09	16.36
PP08	45.33	**PP08**	**45.55**
PP09	19.59	PP07	21.92
PP10	36.85	PP06	36.06
PP11	18.50	PP05	19.08
PP12	39.81	PP04	42.31
PP13	18.64	PP03	17.91
PP14	20.47	PP02	16.15
PP15	25.01	PP01	0.96
PP16	39.78	**สูงสุด**	**45.55**
		เฉลี่ย	**26.03**

ข1.6 กรณีใช้สายเคเบิลที่มีความต้านทานเท่ากับค่าความต้านทานของรางวิ่ง

R_{RT} = 0.0175 Ω/km

ตารางที่ ข.10 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง กรณีใช้ R_{RT} = 0.0175 Ω/km

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.483	729.580	10.825	-0.868	0.051	-0.044
TSS2	2.287	731.235	12.186	-1.279	0.051	-0.043
TSS3	2.451	729.849	13.038	-1.641	0.047	-0.043
TSS4	2.495	729.482	11.933	-0.869	0.039	-0.042
TSS5	2.562	728.912	13.325	-2.297	0.033	-0.040
TSS6	2.506	729.389	12.590	-1.624	0.025	-0.038
TSS7	2.525	729.228	12.959	-2.744	0.022	-0.036
TSS8	2.433	729.999	12.354	-2.055	0.016	-0.032
TSS9	2.308	731.059	12.474	-5.060	0.018	-0.030
TSS10	2.420	730.111	12.236	-2.365	0.016	-0.028
North Bound						
TSS10	2.393	730.344	12.345	-1.954	0.012	-0.023
TSS9	2.316	730.989	12.454	-3.672	0.013	-0.021
TSS8	2.398	730.295	10.749	-0.879	0.011	-0.018
TSS7	2.533	729.160	13.626	-1.938	0.012	-0.012
TSS6	2.450	729.856	10.621	-0.872	0.010	-0.007
TSS5	2.569	728.851	13.680	-1.053	0.013	-0.008
TSS4	2.485	729.561	11.468	-0.821	0.012	-0.010
TSS3	2.435	729.986	13.269	-2.077	0.018	-0.011
TSS2	2.276	731.324	12.019	-1.345	0.019	-0.012
TSS1	0.894	742.779	3.496	-0.820	0.019	-0.012

R_{RT} = *0.047 Ω/km*

ตารางที่ ข.11 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง กรณีใช้ R_{RT} = 0.047 Ω/km

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.483	729.580	10.825	-0.868	0.051	-0.044
TSS2	2.287	731.235	12.186	-1.279	0.051	-0.043
TSS3	2.451	729.849	13.038	-1.641	0.047	-0.043
TSS4	2.495	729.482	11.933	-0.869	0.039	-0.042
TSS5	2.562	728.912	13.325	-2.297	0.033	-0.040
TSS6	2.506	729.389	12.590	-1.624	0.025	-0.038
TSS7	2.525	729.228	12.959	-2.744	0.022	-0.036
TSS8	2.433	729.999	12.354	-2.055	0.016	-0.032
TSS9	2.308	731.059	12.474	-5.060	0.018	-0.030
TSS10	2.420	730.111	12.236	-2.365	0.016	-0.028
North Bound						
TSS10	2.393	730.344	12.345	-1.954	0.012	-0.023
TSS9	2.316	730.989	12.454	-3.672	0.013	-0.021
TSS8	2.398	730.295	10.749	-0.879	0.011	-0.018
TSS7	2.533	729.160	13.626	-1.938	0.012	-0.012
TSS6	2.450	729.856	10.621	-0.872	0.010	-0.007
TSS5	2.569	728.851	13.680	-1.053	0.013	-0.008
TSS4	2.485	729.561	11.468	-0.821	0.012	-0.010
TSS3	2.435	729.986	13.269	-2.077	0.018	-0.011
TSS2	2.276	731.324	12.019	-1.345	0.019	-0.012
TSS1	0.894	742.779	3.496	-0.820	0.019	-0.012

ข.2 แบบจำลองการติดตั้งที่สถานีไฟฟ้าย่อย

ข2.1 ผลการจำลองการติดตั้ง 4 จุดเชื่อมต่อ

ที่ตำแหน่ง 4.401, 9.578, 15.147, 20.924, 26.717, 32.286 และ 37.463 กิโลเมตร ตามลำดับ

ตารางที่ ข.12 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง สถานีไฟฟ้าย่อย 4 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.474	729.655	10.526	-0.813	0.051	-0.042
TSS2	2.287	731.235	12.152	-2.335	0.051	-0.042
TSS3	2.437	729.972	12.559	-1.555	0.046	-0.041
TSS4	2.515	729.306	12.526	-1.838	0.039	-0.040
TSS5	2.551	729.002	12.898	-2.819	0.032	-0.039
TSS6	2.515	729.306	12.816	-2.369	0.025	-0.036
TSS7	2.530	729.179	13.103	-3.630	0.022	-0.034
TSS8	2.425	730.074	12.004	-1.404	0.016	-0.031
TSS9	2.308	731.059	12.460	-5.275	0.018	-0.029
TSS10	2.423	730.085	12.290	-2.858	0.016	-0.027
North Bound						
TSS10	2.390	730.368	12.138	-2.488	0.011	-0.023
TSS9	2.316	730.986	12.505	-5.291	0.013	-0.020
TSS8	2.449	729.868	12.085	-1.937	0.011	-0.017
TSS7	2.517	729.289	13.007	-3.128	0.010	-0.011
TSS6	2.529	729.188	12.868	-2.780	0.011	-0.009
TSS5	2.543	729.072	12.850	-2.421	0.011	-0.008
TSS4	2.520	729.270	12.515	-2.359	0.013	-0.010
TSS3	2.411	730.190	12.382	-1.236	0.015	-0.011
TSS2	2.276	731.328	11.888	-2.352	0.018	-0.011
TSS1	0.884	742.861	3.089	-0.817	0.018	-0.012

ตารางที่ ข.13 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของสถานีไฟฟ้าย่อย 4 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.85	PP15	21.28
PP02	20.32	PP14	20.95
PP03	25.84	PP13	18.29
PP04	41.33	PP12	48.27
PP05	27.56	PP11	26.13
PP06	**56.33**	PP10	48.92
PP07	25.68	PP09	35.93
PP08	47.16	PP08	47.10
PP09	26.05	PP07	27.20
PP10	48.10	PP06	56.24
PP11	22.01	PP05	24.03
PP12	44.96	PP04	41.37
PP13	23.22	PP03	29.58
PP14	23.39	PP02	19.72
PP15	25.95	PP01	1.00
PP16	48.14	**สูงสุด**	**56.33**
		เฉลี่ย	**31.99**

ข2.2 ผลการจำลองการติดตั้ง 6 จุดเชื่อมต่อ

ที่ตำแหน่ง 4.401, 6.835, 9.578, 12.436, 15.147, 20.924, 26.717, 29.428 32.286, 35.029 และ 37.463 กิโลเมตร ตามลำดับ

ตารางที่ ข.14 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง สถานีไฟฟ้าย่อย 6 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.474	729.657	10.514	-0.823	0.051	-0.042
TSS2	2.287	731.236	12.147	-2.532	0.051	-0.042
TSS3	2.430	730.025	12.525	-1.794	0.047	-0.042
TSS4	2.506	729.386	12.095	-0.824	0.039	-0.040
TSS5	2.526	729.213	12.296	-0.824	0.033	-0.039
TSS6	2.500	729.436	12.333	-0.825	0.025	-0.036
TSS7	2.502	729.420	12.163	-0.825	0.020	-0.035
TSS8	2.413	730.172	11.949	-1.469	0.016	-0.031
TSS9	2.308	731.060	12.457	-5.375	0.018	-0.029
TSS10	2.423	730.086	12.282	-3.092	0.016	-0.027
North Bound						
TSS10	2.390	730.369	12.130	-2.753	0.011	-0.023
TSS9	2.316	730.987	12.502	-5.336	0.013	-0.020
TSS8	2.438	729.964	12.030	-2.014	0.011	-0.017
TSS7	2.494	729.491	12.101	-0.819	0.009	-0.011
TSS6	2.511	729.344	12.355	-0.827	0.010	-0.007
TSS5	2.521	729.261	12.258	-0.828	0.011	-0.008
TSS4	2.508	729.371	12.085	-0.827	0.012	-0.010
TSS3	2.404	730.247	12.347	-1.504	0.016	-0.011
TSS2	2.276	731.329	11.883	-2.560	0.018	-0.011
TSS1	0.884	742.863	3.081	-0.827	0.018	-0.012

ตารางที่ ข.15 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อย ของสถานีไฟฟ้าย่อย 6 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	19.84	PP15	21.28
PP02	20.31	PP14	20.94
PP03	25.59	PP13	18.17
PP04	38.99	PP12	46.95
PP05	24.20	PP11	21.61
PP06	35.99	PP10	32.37
PP07	25.53	PP09	35.82
PP08	42.19	PP08	42.18
PP09	23.33	PP07	23.89
PP10	32.30	PP06	35.70
PP11	21.59	PP05	24.18
PP12	42.43	PP04	39.16
PP13	23.20	PP03	29.55
PP14	23.39	PP02	19.64
PP15	25.93	PP01	1.00
PP16	**48.04**	**สูงสุด**	**48.04**
		เฉลี่ย	**28.55**

ภาคผนวก ค

ผลการจำลองกรณีศึกษาที่ 2 (รถไฟฟ้าขบวนเดียว MRT สายสีม่วงเหนือ)

ระบบติดตั้งตัวแปลงความต้านทานเชิงลบ

ค.1 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวแปลงความต้านทานเชิงลบ

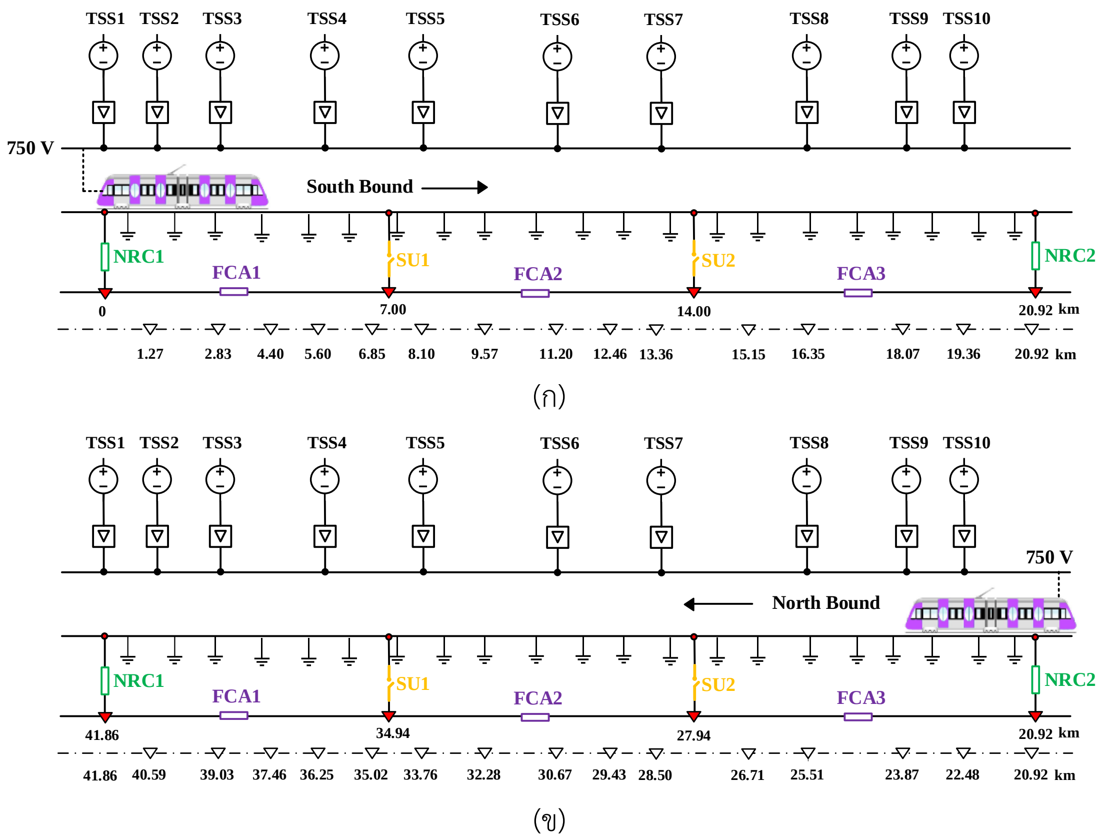
ค1.1 ผลการจำลองการติดตั้งจุดเชื่อมต่อ 3 จุดเชื่อมต่อ

ตารางที่ ค.1 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 3 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.431	730.017	45.363	-6.193	0.788	-0.300
TSS2	2.285	731.248	40.321	-7.952	0.776	-0.299
TSS3	2.459	729.782	35.536	-8.292	0.750	-0.295
TSS4	2.555	728.970	27.393	-6.183	0.684	-0.285
TSS5	2.567	728.870	20.107	-6.182	0.611	-0.273
TSS6	2.477	729.628	12.087	-9.920	0.509	-0.255
TSS7	2.546	729.044	13.925	-14.499	0.433	-0.240
TSS8	2.460	729.773	13.511	-12.181	0.325	-0.215
TSS9	2.308	731.057	12.337	-10.594	0.268	-0.199
TSS10	2.430	730.029	11.121	-9.228	0.221	-0.185
North Bound						
TSS10	2.400	730.283	11.422	-9.423	0.120	-0.148
TSS9	2.317	730.984	12.447	-16.233	0.078	-0.130
TSS8	2.484	729.568	13.654	-17.150	0.033	-0.107
TSS7	2.535	729.142	13.809	-17.233	0.011	-0.063
TSS6	2.477	729.632	11.690	-17.217	0.010	-0.083
TSS5	2.562	728.911	13.008	-17.202	0.026	-0.135
TSS4	2.559	728.939	14.091	-17.197	0.063	-0.169
TSS3	2.435	729.984	17.419	-17.195	0.100	-0.197
TSS2	2.277	731.323	22.508	-17.198	0.115	-0.207
TSS1	0.856	743.089	27.456	-17.203	0.122	-0.212

ค1.2 แบบจำลองและผลการจำลองการติดตั้งจุดเชื่อมต่อตัวนำ 4 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



รูปที่ ค.1 แบบจำลองการติดตั้งตัวแปลงความต้านทานเชิงลบ 4 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ค.2 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 4 จุดเชื่อมต่อ

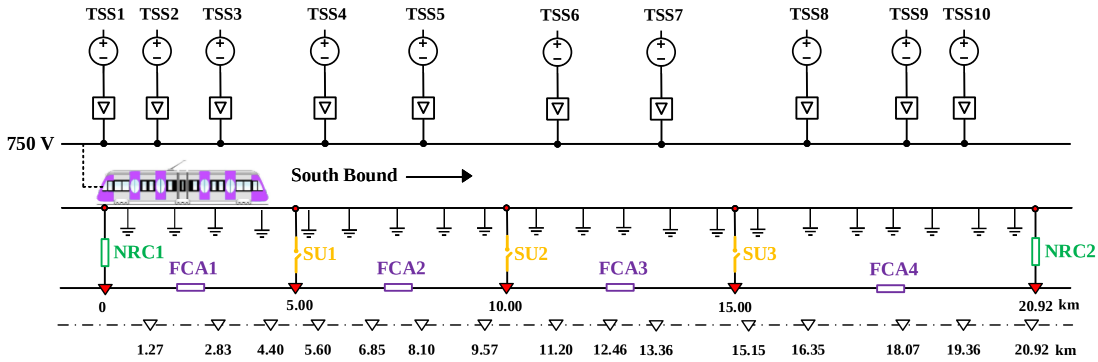
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.393	730.340	45.365	-7.551	0.787	-0.326
TSS2	2.285	731.253	40.323	-7.558	0.775	-0.324
TSS3	2.459	729.782	35.538	-7.566	0.749	-0.320
TSS4	2.508	729.371	27.395	-9.885	0.683	-0.309
TSS5	2.529	729.193	20.109	-14.986	0.610	-0.295
TSS6	2.540	729.095	13.541	-18.004	0.508	-0.274
TSS7	2.513	729.328	9.177	-15.897	0.432	-0.256
TSS8	2.455	729.820	12.828	-12.434	0.324	-0.227
TSS9	2.308	731.058	12.263	-10.518	0.267	-0.209
TSS10	2.430	730.029	11.112	-8.905	0.220	-0.192
North Bound						
TSS10	2.400	730.283	11.411	-9.421	0.119	-0.150
TSS9	2.317	730.985	12.360	-16.231	0.077	-0.129
TSS8	2.478	729.618	12.859	-17.147	0.032	-0.102
TSS7	2.506	729.386	9.902	-17.232	0.008	-0.070
TSS6	2.553	728.986	13.661	-17.228	0.011	-0.083
TSS5	2.515	729.305	12.815	-17.214	0.035	-0.136
TSS4	2.516	729.299	11.739	-17.206	0.073	-0.170
TSS3	2.435	729.984	17.872	-17.203	0.109	-0.198
TSS2	2.275	731.335	21.615	-17.204	0.123	-0.208
TSS1	0.839	743.227	25.244	-17.208	0.130	-0.213

ตารางที่ ค.3 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้ง 4 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	16.22	PP15	20.85
PP02	19.60	PP14	20.85
PP03	28.85	PP13	19.45
PP04	61.19	PP12	60.23
PP05	20.63	PP11	24.39
PP06	36.65	PP10	47.04
PP07	28.84	PP09	23.77
PP08	**70.38**	PP08	70.05
PP09	25.78	PP07	23.67
PP10	46.06	PP06	26.99
PP11	16.17	PP05	27.54
PP12	59.02	PP04	62.00
PP13	23.49	PP03	29.68
PP14	23.00	PP02	16.89
PP15	24.06	PP01	0.28
PP16	47.28	**สูงสุด**	**70.38**
		เฉลี่ย	**32.93**

ค1.3 แบบจำลองการติดตั้งจุดเชื่อมต่อ 5 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



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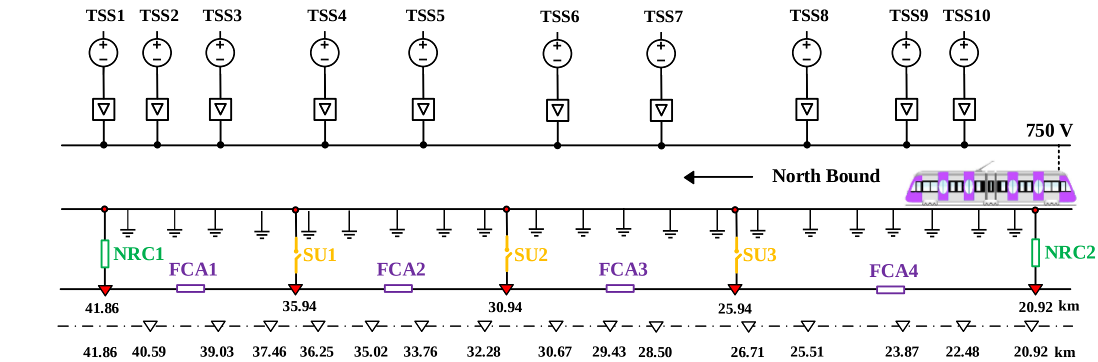


(ข)

รูปที่ ค.2 แบบจำลองการติดตั้งตัวแปลงความต้านทานเชิงลบ 5 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ค.4 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 5 จุดเชื่อมต่อ

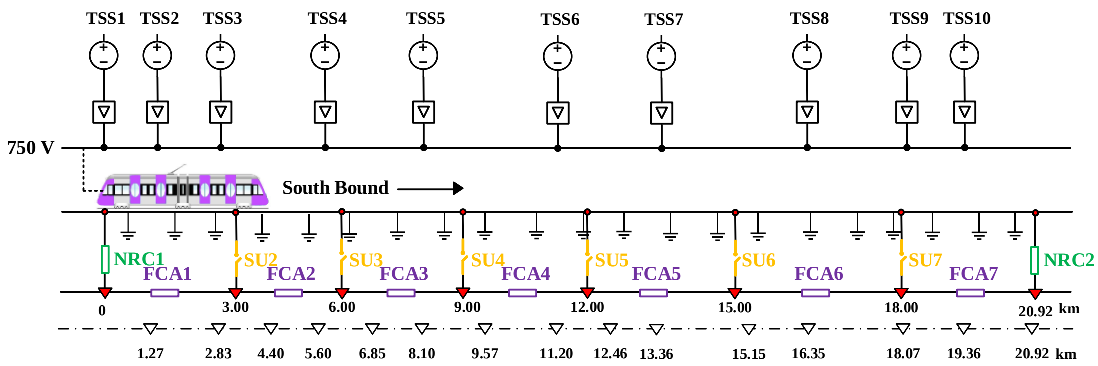
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.349	730.716	45.360	-21.709	0.790	-0.673
TSS2	2.285	731.249	40.318	-21.829	0.779	-0.667
TSS3	2.443	729.918	35.532	-21.918	0.752	-0.654
TSS4	2.435	729.982	27.389	-21.501	0.686	-0.619
TSS5	2.571	728.836	20.103	-14.280	0.614	-0.577
TSS6	2.477	729.633	11.054	-11.668	0.512	-0.516
TSS7	2.517	729.295	10.229	-15.742	0.436	-0.469
TSS8	2.436	729.980	11.371	-11.496	0.328	-0.394
TSS9	2.249	731.558	8.913	-10.625	0.270	-0.350
TSS10	2.429	730.039	10.680	-11.455	0.224	-0.310
North Bound						
TSS10	2.400	730.283	11.377	-11.446	0.123	-0.217
TSS9	2.316	730.991	12.096	-16.236	0.081	-0.175
TSS8	2.419	730.119	10.236	-17.153	0.036	-0.126
TSS7	2.533	729.159	12.875	-17.239	0.008	-0.043
TSS6	2.445	729.905	12.327	-17.225	0.022	-0.080
TSS5	2.570	728.843	17.500	-17.200	0.099	-0.132
TSS4	2.559	728.939	21.666	-17.183	0.153	-0.166
TSS3	2.435	729.984	26.328	-17.170	0.201	-0.194
TSS2	2.276	731.323	29.102	-17.165	0.220	-0.204
TSS1	0.855	743.094	31.794	-17.164	0.228	-0.209

ตารางที่ ค.5 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัวแปลงความต้านทานเชิงลบ 5 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	16.35	PP15	20.88
PP02	19.76	PP14	20.98
PP03	26.30	PP13	20.47
PP04	41.84	**PP12**	**66.72**
PP05	27.07	PP11	26.17
PP06	55.10	PP10	48.39
PP07	23.60	PP09	18.50
PP08	47.12	PP08	63.03
PP09	17.03	PP07	27.66
PP10	39.32	PP06	57.01
PP11	18.54	PP05	28.67
PP12	47.45	PP04	62.82
PP13	21.93	PP03	29.56
PP14	20.99	PP02	16.57
PP15	23.80	PP01	0.26
PP16	47.28	**สูงสุด**	**66.72**
		เฉลี่ย	**32.29**

ค1.4 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวแปลงความต้านทานเชิงลบ 8 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



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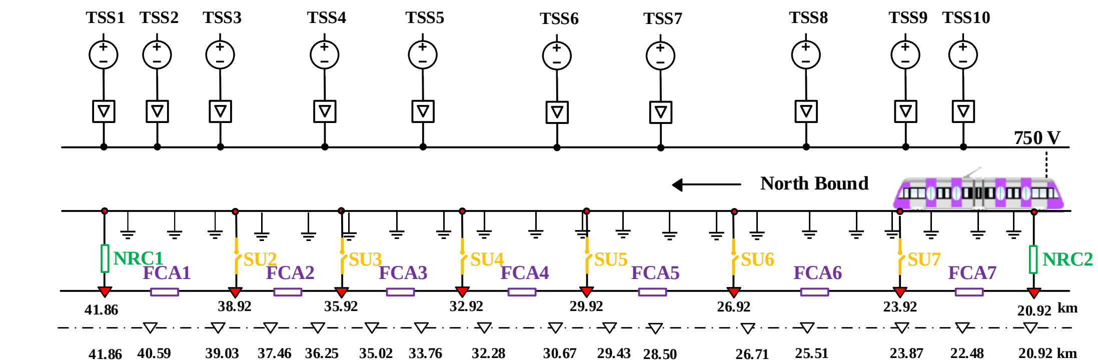


รูปที่ ค.3 แบบจำลองการติดตั้งตัวแปลงความต้านทานเชิงลบ 8 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ค.6 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 8 จุดเชื่อมต่อ

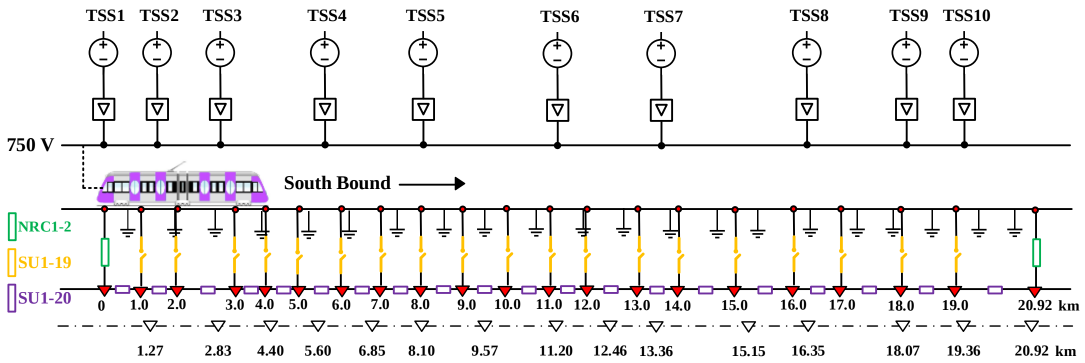
South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.241	731.625	45.155	-11.283	0.780	-0.539
TSS2	2.287	731.235	40.114	-11.458	0.769	-0.536
TSS3	2.142	732.457	35.328	-11.420	0.743	-0.530
TSS4	2.519	729.275	27.186	-11.539	0.677	-0.512
TSS5	2.547	729.040	19.900	-11.649	0.605	-0.490
TSS6	2.506	729.387	12.413	-11.789	0.503	-0.456
TSS7	2.517	729.295	10.229	-11.889	0.428	-0.428
TSS8	2.436	729.980	11.371	-12.032	0.323	-0.381
TSS9	2.249	731.558	8.913	-12.111	0.270	-0.352
TSS10	2.429	730.039	10.679	-12.173	0.227	-0.324
North Bound						
TSS10	2.399	730.294	10.912	-12.211	0.131	-0.254
TSS9	2.250	731.550	8.415	-16.462	0.093	-0.220
TSS8	2.456	729.806	11.176	-17.286	0.051	-0.175
TSS7	2.505	729.390	10.421	-17.228	0.001	-0.091
TSS6	2.520	729.270	9.687	-19.158	0.011	-0.082
TSS5	2.543	729.075	11.636	-19.060	0.057	-0.133
TSS4	2.527	729.207	20.355	-18.501	0.120	-0.165
TSS3	2.164	732.271	30.144	-17.836	0.178	-0.192
TSS2	2.277	731.315	35.966	-17.443	0.202	-0.202
TSS1	0.780	743.708	41.612	-17.065	0.213	-0.206

ตารางที่ ค.7 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัวแปลงความต้านทานเชิงลบ 8 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	16.62	PP15	19.81
PP02	19.59	PP14	16.84
PP03	24.64	PP13	17.41
PP04	56.34	PP12	47.69
PP05	21.62	PP11	22.46
PP06	50.00	PP10	39.89
PP07	18.52	PP09	19.74
PP08	57.17	PP08	56.88
PP09	17.41	PP07	28.44
PP10	39.32	PP06	50.21
PP11	18.31	PP05	25.03
PP12	47.45	**PP04**	**57.54**
PP13	21.93	PP03	15.89
PP14	20.99	PP02	17.52
PP15	23.8	PP01	0.22
PP16	47.07	**สูงสุด**	**57.54**
		เฉลี่ย	**30.20**

ค1.5 แบบจำลองการติดตั้งจุดเชื่อมต่อตัวแปลงความต้านทานเชิงลบ 21 จุดเชื่อมต่อ

แบบจำลองการติดตั้งจุดเชื่อมต่อ



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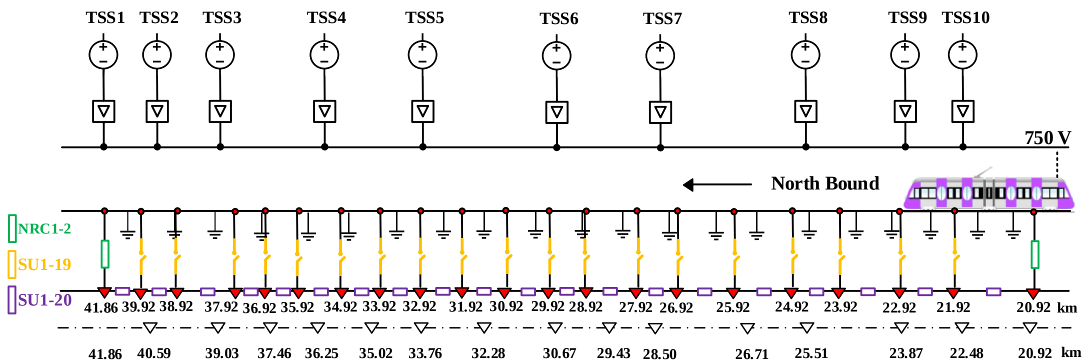

(ข)

รูปที่ ค.4 แบบจำลองการติดตั้งตัวแปลงความต้านทานเชิงลบ 21 จุดเชื่อมต่อ

(ก) ทิศทาง South Bound (ข) ทิศทาง North Bound

ตารางที่ ค.8 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง 21 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.260	731.458	37.502	-7.085	0.481	-0.494
TSS2	2.049	733.233	32.573	-11.476	0.474	-0.493
TSS3	2.340	730.784	27.892	-15.304	0.460	-0.487
TSS4	2.407	730.223	19.927	-16.775	0.423	-0.469
TSS5	2.422	730.098	13.450	-15.481	0.382	-0.445
TSS6	2.426	730.060	9.009	-17.433	0.324	-0.407
TSS7	2.449	729.864	6.836	-19.254	0.279	-0.372
TSS8	2.381	730.438	7.329	-15.466	0.213	-0.316
TSS9	2.242	731.617	7.516	-15.981	0.177	-0.282
TSS10	2.396	730.319	8.472	-15.628	0.146	-0.251
North Bound						
TSS10	2.343	730.766	7.057	-16.199	0.078	-0.203
TSS9	2.243	731.608	7.168	-20.297	0.050	-0.185
TSS8	2.398	730.295	7.367	-19.006	0.019	-0.159
TSS7	2.434	729.993	7.133	-18.868	0.001	-0.104
TSS6	2.427	730.057	9.534	-18.342	0.014	-0.090
TSS5	2.399	730.286	13.916	-13.687	0.076	-0.101
TSS4	2.398	730.297	17.446	-14.311	0.120	-0.116
TSS3	2.318	730.976	22.990	-13.319	0.159	-0.131
TSS2	2.051	733.219	28.735	-9.050	0.175	-0.135
TSS1	1.149	740.689	34.306	-6.560	0.181	-0.136

ตารางที่ ค.9 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของระบบติดตั้งตัวแปลงความต้านทานเชิงลบ 21 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	17.26	PP15	14.63
PP02	13.02	PP14	14.69
PP03	16.36	PP13	13.18
PP04	33.28	**PP12**	**39.65**
PP05	16.09	PP11	16.56
PP06	32.35	PP10	32.01
PP07	17.44	PP09	24.95
PP08	37.70	PP08	37.91
PP09	16.46	PP07	18.11
PP10	31.67	PP06	30.43
PP11	14.24	PP05	18.51
PP12	39.62	PP04	33.57
PP13	15.17	PP03	21.27
PP14	17.97	PP02	13.38
PP15	22.51	PP01	0.44
PP16	39.38	**สูงสุด**	**39.65**
		เฉลี่ย	**22.89**

ค.2 แบบจำลองการติดตั้งที่สถานีไฟฟ้าย่อย

ค2.1 ผลการจำลองการติดตั้ง 4 จุดเชื่อมต่อ

ที่ตำแหน่ง 4.401, 9.578, 15.147, 20.924, 26.717, 32.286 และ 37.463 กิโลเมตร ตามลำดับ

ตารางที่ ค.10 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง สถานีไฟฟ้าย่อย 4 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.346	730.735	45.795	-25.323	0.827	-0.808
TSS2	2.286	731.244	39.178	-25.434	0.818	-0.802
TSS3	2.416	730.146	34.482	-25.525	0.795	-0.786
TSS4	2.479	729.610	26.513	-25.030	0.739	-0.744
TSS5	2.567	728.869	20.640	-19.664	0.675	-0.693
TSS6	2.509	729.357	14.710	-19.199	0.584	-0.620
TSS7	2.537	729.120	11.689	-17.898	0.513	-0.562
TSS8	2.430	730.028	11.598	-16.938	0.409	-0.478
TSS9	2.308	731.060	12.148	-16.098	0.351	-0.434
TSS10	2.432	730.013	11.277	-12.300	0.301	-0.392
North Bound						
TSS10	2.398	730.297	11.249	-12.286	0.190	-0.293
TSS9	2.316	730.988	12.206	-16.215	0.142	-0.247
TSS8	2.454	729.824	11.615	-17.081	0.089	-0.190
TSS7	2.525	729.223	11.690	-17.623	0.008	-0.098
TSS6	2.523	729.241	14.860	-20.044	0.030	-0.080
TSS5	2.559	728.934	20.873	-20.549	0.122	-0.135
TSS4	2.485	729.562	26.448	-24.922	0.186	-0.182
TSS3	2.390	730.369	34.479	-25.465	0.243	-0.224
TSS2	2.276	731.324	39.268	-25.380	0.265	-0.240
TSS1	0.821	743.375	44.806	-25.282	0.275	-0.246

ตารางที่ ค.11 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อย ของสถานีไฟฟ้าย่อย 4 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	16.53	PP15	20.76
PP02	19.80	PP14	20.64
PP03	23.43	PP13	17.75
PP04	36.99	PP12	46.47
PP05	27.25	PP11	25.24
PP06	**55.02**	PP10	47.74
PP07	22.13	PP09	35.91
PP08	46.99	PP08	48.75
PP09	25.63	PP07	25.92
PP10	46.98	PP06	54.87
PP11	20.07	PP05	24.31
PP12	42.88	PP04	39.96
PP13	22.90	PP03	29.26
PP14	22.96	PP02	17.20
PP15	24.41	PP01	0.30
PP16	47.12	**สูงสุด**	**55.02**
		เฉลี่ย	**30.84**

ค2.2 ผลการจำลองการติดตั้ง 6 จุดเชื่อมต่อ

ที่ตำแหน่ง 4.401, 6.835, 9.578, 12.436, 15.147, 20.924, 26.717, 29.428 32.286, 35.029 และ 37.463 กิโลเมตร ตามลำดับ

ตารางที่ ค.12 กำลังไฟฟ้า แรงดันไฟฟ้า และศักย์ไฟฟ้าที่ราง สถานีไฟฟ้าย่อย 6 จุดเชื่อมต่อ

South Bound						
TSS	$P_{S,max}$(MW)	$V_{C,min}$(V)	$U_{RE,max}$(V)	$U_{RE,min}$(V)	$U_{SE,max}$(V)	$U_{SE,min}$(V)
TSS1	2.346	730.735	45.343	-23.092	0.805	-0.781
TSS2	2.286	731.244	39.950	-23.937	0.795	-0.776
TSS3	2.416	730.146	35.228	-24.715	0.773	-0.761
TSS4	2.469	729.699	27.193	-25.603	0.718	-0.723
TSS5	2.520	729.266	20.886	-19.656	0.655	-0.676
TSS6	2.500	729.437	14.873	-20.062	0.564	-0.606
TSS7	2.499	729.444	10.672	-18.873	0.495	-0.551
TSS8	2.430	730.028	11.649	-17.413	0.393	-0.476
TSS9	2.308	731.060	12.162	-16.529	0.335	-0.432
TSS10	2.432	730.013	11.243	-12.646	0.287	-0.390
North Bound						
TSS10	2.398	730.297	11.275	-12.557	0.178	-0.291
TSS9	2.316	730.988	12.216	-16.136	0.131	-0.245
TSS8	2.454	729.824	11.597	-17.047	0.080	-0.188
TSS7	2.490	729.524	10.199	-18.006	0.006	-0.103
TSS6	2.512	729.334	14.458	-20.456	0.027	-0.081
TSS5	2.516	729.305	20.555	-20.138	0.118	-0.133
TSS4	2.474	729.658	26.615	-25.056	0.181	-0.179
TSS3	2.390	730.369	34.712	-24.236	0.238	-0.217
TSS2	2.276	731.324	39.527	-23.462	0.260	-0.231
TSS1	0.821	743.375	44.198	-22.683	0.270	-0.237

ตารางที่ ค.13 ค่าศักย์ไฟฟ้าที่รางสูงสุดสถานีไฟฟ้าย่อยของสถานีไฟฟ้าย่อย 6 จุดเชื่อมต่อ

South bound		North bound	
Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)	Passenger Station	ศักย์ไฟฟ้ารางสูงสุด (V)
PP01	16.53	PP15	20.63
PP02	19.67	PP14	20.64
PP03	23.43	PP13	17.42
PP04	36.02	PP12	46.47
PP05	19.95	PP11	20.94
PP06	36.88	PP10	35.02
PP07	21.55	PP09	34.07
PP08	45.96	**PP08**	**47.64**
PP09	20.32	PP07	22.71
PP10	32.33	PP06	38.45
PP11	18.66	PP05	22.58
PP12	42.92	PP04	38.50
PP13	22.90	PP03	29.26
PP14	22.87	PP02	17.25
PP15	24.41	PP01	0.29
PP16	47.12	**สูงสุด**	**47.64**
		เฉลี่ย	**27.85**

ภาคผนวก ง

บทความวิชาการที่ได้รับการตีพิมพ์เผยแพร่ในระหว่างศึกษา

รายชื่อบทความวิชาการที่ได้รับการตีพิมพ์เผยแพร่

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Reducing Rail Potential and Stray Current with NEG-TPS in DC Electrified Railways

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***Abstract*— This article contains an NEG-TPS that provides zero-resistance loops, to reduce the rail potential and stray current in DC electrified railways. The NEG-TPS are built by directly adding power electronic devices in a traditional traction power system without altering the trains, rails, or tunnels. As the results, obtained from the simulations based on the case study. The percentage of rail potential that is reduced ranges from 81.2% to 100% when compared to TRA-TPS, and ranges from 0.9% to 26.3% when compared to RET-TPS, and the reduction percentage of stray current mainly ranges from 90.6% to 100% when compared to TRA-TPS, and ranges from 1.0% to 26.4% when compared to RET-TPS.**

Keywords—Rail potential, Stray current, Negative resistance converter (NRC), DC electrified railways, Return conductor.

NOMENCLATURE

NEG-TPS	Negative resistance converter traction power system.
TRA-TPS	Traditional traction power system.
RET-TPS	Return conductor traction power system.
NRC	Negative resistance converter.
FCA	Feeder cable.
SU	Switch unit.
u_r	Voltage of zero-resistance loop.
u_{NRC}	Output voltage of NRC.
u_{FCA}	Voltage across FCA.
u_{SU}	Conducting voltage drop of SU.
u_{rT}	Rail potential of TRA-TPS.
u_{rR}	Rail potential of RET-TPS.
u_{rN}	Rail potential of NEG-TPS.
i_{rT}	Stray current of TRA-TPS.
i_{rR}	Stray current of RET-TPS.
i_{rN}	Stray current of NEG-TPS.
η	Reduction percentage of rail potential.
δ	Reduction percentage of stray current.

I. INTRODUCTION

At present the DC electrified railways systems are widely used for transportation especially in the Bangkok, Thailand because they can handle with the crowded passengers during peak times. Most of the main transportation with railways in Bangkok are the DC electrified railways which is high opportunity to occur the problems of the rail potential and the stray current. These problems are danger to the building structures at the substations and the substations nearby where is constructed with the metal. The problem of stray current into the ground is an unavoidable problem [1]. The rail current returns to the substation through the running rail. Some of the reverse currents leak into the earth and the metal construction. It is a significant factor in the corrosion of the track's metal which affect the reduction of running track life, grounded equipment, and strengthen buildings. Every year, 1 A of stray current may corrode 9 kg of steel, 34 kg of lead, and 34 kg of copper, according to research [2]. One of the performed solutions, nowadays, Parallel conductors were placed along the running rails to share the rail current and minimize the longitudinal resistance of rails, lowering the rail potential and stray current. This system has limitations on an amount of the cable length and cost. The effect of the rail potential and stray current is not as apparent as it should be if the number of cables is insufficient [3].

Therefore, this paper presents a new method to decrease the rail potential and the stray current which is called the NEG – TPS by using zero resistance in a loop to reduce the rail current's return path on the running rails [4]. The rail potential and the stray current are effectively decreased by the NEG-TPS. It also provides an DC electrified railways safety without reconstruction the existing structure.

The remainder of this article is arranged in the following manner. the configuration and operation principles of NEG-TPS are discussed in depth in section II. The case study model is discussed in Section III. The modeling results and reduction performance of rail potential and stray current are shown in Section IV. Finally, Section V has the conclusion.

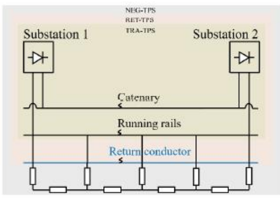

Fig. 1. Configuration of TRA-TPS, RET-TPS and NEG-TPS.

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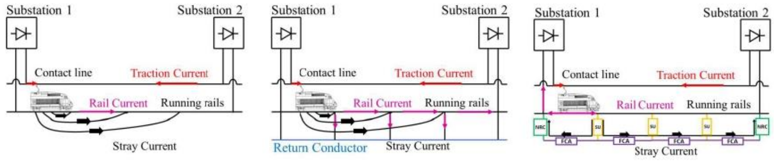

Fig. 2. Rail return current configurations between two substations. (a) TRA-TPS (b) RET-TPS (c) NEG-TPS.

II. Configurations and Operation Principles

Traction power systems are made up of traction substations, contact lines/catenary, and running rails, with the arrangement varying of TRA-TPS, RET-TPS and NEG-TPS are shown in Fig. 1 and Fig. 2. The rail potential and stray current calculations on the running rails when the train moves from the traction substation 1 (TS1) to the traction substation 2 (TS2) as shown in Fig. 3, are obtained by the Kirchhoff's current law (KCL) and the Kirchhoff's voltage law (KVL) [4].

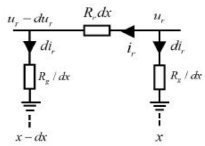

Fig. 3. Differential circuit of running rails.

A. Traditional Traction Power System

In TRA-TPS, as shown in Fig. 2(a). When the train moves from TS1 to TS2, the traction current supplies to the train via the contact line or the third rail located parallel to the running rail. The electricity will flow into the electric train to supply the traction system and the rail current will then return to the substation. The stray current also flows through the earth back to the substation.

Regarding Fig. 3, the rail potential, u_{rC} and the stray current, i_{sC} in TRA-TPS, where A_k and B_k are parameters determined by using KVL and KCL boundary conditions, are calculated as follows:

$$\begin{cases} u_{rT(k)} = R_g\left(A_k e^{x\sqrt{\frac{R_r}{R_g}}} + B_k e^{-x\sqrt{\frac{R_r}{R_g}}}\right), \quad 2 \le k \le n \\ i_{sT} = \dfrac{1}{2R_g}\displaystyle\int_0^L \sum_{k=2}^{k=n} \left|u_{rT(k)}\right| dx = \dfrac{u_{rT(k)}}{R_g} \end{cases} \tag{1}$$

B. Return Conductor Traction Power System

In RET-TPS, as shown in Fig. 2(b). The return conductors are installed parallel to the running rail and connected to the running track for the specified distance. The most of the rail currents are consequently returned to substations via the return conductors [5]. Therefore, the rail current that leaked from the rail to the ground is reduced.

Considering Fig. 2, the rail potential, u_{rN} and the stray current, i_{sN} in RET-TPS, where G_k and H_k are parameters determined by using KVL and KCL boundary conditions are expressed as follows:

$$\begin{cases} u_{rR(k)} = R_g\left(G_k e^{x\sqrt{\frac{R_r}{R_g}}} + H_k e^{-x\sqrt{\frac{R_r}{R_g}}}\right), \quad 1 \le k \le n \\ i_{sR} = \dfrac{1}{2R_g}\displaystyle\int_0^L \sum_{k=1}^{k=n} \left|u_{rR(k)}\right| \; dx = \dfrac{u_{rR(k)}}{R_g} \end{cases} \tag{2}$$

C. Negative Resistance Converter Traction Power System

In NEG-TPS, as shown in Fig. 2(c). NRCs, FCAs and SUs are added to the TRA-TPS. SUs at both ends of a rail segment are activated when a train passes through is activated, providing a shorter path of the return current. To get the voltage in the loop to zero, the output voltage of NRCs is controlled to equal the polar opposite of the voltage between FCAs and SUs on this new return path. The resistance of the turned-on SUs to NRCs should then be zero ideally.

The NRC is a negative equivalent output resistance bipolar full-bridge DC–DC converter and a flexible controllable output voltage as shown in Fig. 4(a). SU stands for a bidirectional switch, which is two IGBTs linked in reverse series shown in Fig. 4(b). FCA stands for parallel cables, which is comparable to resistors in parallel shown in Fig. 4(c), NRCs and SUs are devices that allow energy to flow in both directions.

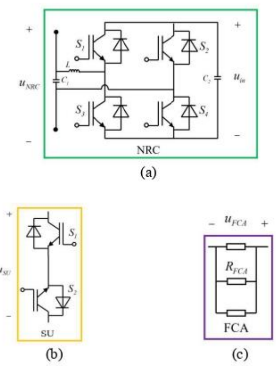

Fig. 4. Operation devices in NEG-TPS. (a) NRC. (b) SU. (c) FCA.

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The length of each rail section is determined by the various rail potential and stray current reduction requirements. In this article, there are four rail sections in the running rails to make the simplified analysis which the output resistances of NRCs are calculated as in (3) and (4). Regarding Fig. 3, the rail potential, u_{rN} and the stray current, i_{sN} in NEG-TPS, where G_k and H_k are parameters determined by using KVL and KCL boundary conditions, are obtained as in (5).

$$u_{NRC1} \equiv \begin{cases} -u_{FCA1} - u_{SU1}, & k = 1 \\ -\sum_{j=1}^{j=k-1} u_{FCAj} - u_{SU(k-1)}, & 2 \le k \le n \end{cases}$$

$$\text{So } R_{NRC1} = \frac{u_{NRC1}}{i_{NRC1}} \tag{3}$$

$$R_{NRC1} = \begin{cases} -R_{FCAj} - R_{SU1}, & k = 1 \\ -\sum_{j=1}^{j=k-1} R_{FCAj} - R_{SU(k-1)} & 2 \le k \le n \end{cases}$$

$$u_{NRC2} = \begin{cases} \sum_{j=k+1}^{j=n} u_{FCAj} - u_{SU(k)}, & 1 \le k \le n-1 \\ u_{FCA(n)} - u_{SU(n-1)}, & k = n \end{cases}$$

$$\text{So } R_{NRC2} = \frac{u_{NRC2}}{i_{NRC2}} \tag{4}$$

$$R_{NRC2} = \begin{cases} -\sum_{j=k+1}^{j=n} R_{FCAj} - R_{SU(k)}, & 1 \le k \le n-1 \\ -R_{FCA(n)} - R_{SU(n-1)}, & k = n \end{cases}$$

$$\begin{cases} u_{rN(k)} = R_g (G_k e^{x\sqrt{\frac{R_r}{R_g}}} + H_k e^{-x\sqrt{\frac{R_r}{R_g}}}), \ 1 \le k \le n \\ i_{sN} = \frac{1}{2R_g} \int_0^L \sum_{k=1}^{k=n} \left| u_{rN(k)} \right| dx = \frac{u_{rN(k)}}{R_g} \end{cases} \tag{5}$$

III. Case Study Modelling

In this article, the DC electrified railway system of the case study includes a single train running on the track section and three substations located at a position of 0, 5, and 10 km, respectively. TABLE. I. lists the modelling parameters of the typical equivalent circuit of the case study as shown in Fig. 5. The substation voltage rated at 1500 V which traction current is also constant at 1667 A. The simulation results are obtained by applying MATLAB program.

TABLE I. Modelling Parameters

Parameters	Variables	Values	Units
Substation voltage rated	u_{subs}	1500	V
Train current	i_L	1667	A
Catenary resistance(OCS)	R_C	75	mΩ/km
Running rail resistance	R_r	9	mΩ/km
SU resistance	R_{SU}	0.002	mΩ/km
FCA resistance	R_{FCA}	0.00225	mΩ/km
Rail-to-earth resistance	R_g	2	Ω·km
Distance	L	10	km

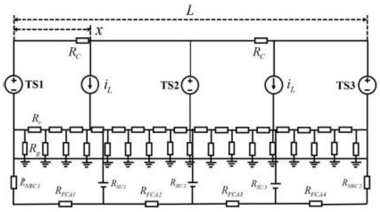


Fig. 5. Typical equivalent circuit of TRA-TPS, RET-TPS and NEG-TPS.

Considering the models of NEG-TPS, RET-TPS, and TRA-TPS shown in Fig. 2, the rail potential and the stray current are obtained from (1), (2), and (5), respectively. The assessments of the reduction performance of NEG-TPS in terms of the distribution of the rail potential and the stray current are reasonably examined in the next section.

IV. Results and Discussions

A. Rail Potential and Stray Current Distributions

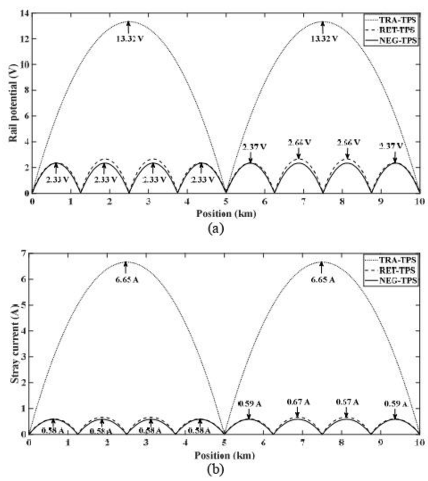


Fig. 6. Case study results. (a) Rail potential in TRA-TPS, RET-TPS and NEG-TPS. (b) Stray current in TRA-TPS, RET-TPS and NEG-TPS.

From Fig. 6, x is represented the train position. In TRA-TPS, the maximum rail potential, u_{rT} is 13.32 V as presented in in Fig. 6(a), where x are at 2.50 km and 7.50 km. The train is now in the center of two substations where the maximum of u_{rT} occurs at these train locations. The maximum stray current, i_{sT} is 6.65 A as presented in Fig. 6(b), where x are at 2.50 km and 7.50 km. At this point, the train is also in the center between substations where the maximum of i_{sT} also occurs at these train locations.

In RET-TPS, the maximum rail potential, u_{rR} is 2.66 V as presented in Fig. 6(a), when the train is in the center of the rail-section 2, 3, 6 and 7, where x are at 1.88 km, 3.14 km, 6.88 km and 8.14 km, respectively. The maximum stray current, i_{sR} is 0.67 A as presented in Fig. 6(b), when the train is also in the center of the rail-section 2, 3, 6 and 7, where x are at 1.88 km, 3.14 km, 6.88 km and 8.14 km, respectively.

In NEG-TPS, the maximum rail potential, u_{rN} is 2.33 V as presented in Fig. 6(a), when the train is in the center of each rail section where x are at 0.62 km, 1.88 km, 3.14 km, 4.38 km, 5.62 km, 6.88 km, 8.14 km and 9.38 km. Because the running rails are evenly divided into four rail sections, the rail potential distribution at the train site is same in each rail section. The maximum stray current, i_{sN} is about 0.58 A when the train is in the center of each rail section, as shown in Fig. 6(b). u_{rN} properly distributed in the rail section with a length of $L/8$. Whereas i_{sN} is dispersed across the whole running rails.

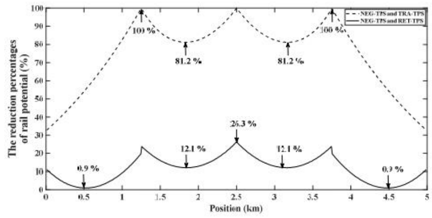
B. Reduction Performance of Rail Potential and Stray Current

The percentage of reduction of the rail potential, η and the stray current, δ are defined in (6) and (7) with the intention of examining NEG-TPS reduction performance during the train services, where η_{NT} is the percentage of reduction of the rail potential between NEG-TPS and TRA-TPS, η_{NR} is the percentage of reduction of the rail potential between NEG-TPS and RET-TPS, δ_{NT} is the percentage of reduction of the stray current between NEG-TPS and TRA-TPS and δ_{NR} is the percentage of reduction of the stray current between NEG-TPS and RET-TPS.

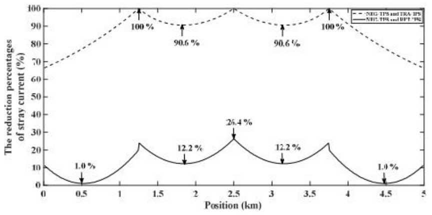
$$\eta = \begin{cases} \eta_{NT} = (1 - \dfrac{u_{rN}}{u_{rT}}) \times 100\% \\ \eta_{NR} = (1 - \dfrac{u_{rN}}{u_{rR}}) \times 100\% \end{cases} \tag{6}$$

$$\delta = \begin{cases} \delta_{NT} = (1 - \dfrac{i_{rN}}{u_{rT}}) \times 100\% \\ \delta_{NR} = (1 - \dfrac{i_{rN}}{u_{rR}}) \times 100\% \end{cases} \tag{7}$$

From the simulation results as shown in Fig. 7, the track range of 0-5 km are only used to analyze the percentage of reduction of the rail potential and the stray current, because the results of the assessment are the same as the second half of the track. In NEG-TPS, the maximum rail potential and stray current are reduced by 81.2% and 90.6% in comparison with TRA-TPS, respectively. In additions, the maximum rail potential and stray current are reduced by 26.3% and 26.4% in NEG-TPS in comparison with RET-TPS, respectively.



(a)



(b)

Fig. 7. Percentage of reduction. (a) Rail potential in TRA-TPS, RET-TPS and NEG-TPS. (b) Stray current in TRA-TPS, RET-TPS and NEG-TPS.

V. Conclusion

In DC electrified railways, the NEG-TPS system is proposed to reduce rail potential and stray current. The NEG-TPS system's running rails are split into four rail sections, and the rail current is zero in the section that is no train services. As a result, it is found that the rail potential and the stray current are reduced obviously in NEG-TPS. In the meantime, NEG-TPS requires no modifications to the trains, tracks, tunnels, or other infrastructure. The percentage of reductions are also used to verify the reduction performance of the rail potential and the stray current of the NEG-TPS. Furthermore, the NEG-TPS is possibly used in both the present and the future of DC electrified railways.

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Evaluation of rail potential and stray current reduction by using NEG-ETP in DC railway system

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Abstract

The NEG-ETP system that providing zero resistance closed circuit reducing the reverse path of current on the running rail is presented in this article. The NEG-ETP system is created by installing additional electronics in conventional electrical systems. Without modifying trains, tracks, or tunnels. Using MATLAB program through models for MRT purple line (North), rail potential and stray current are assessed in accordance with EN 50122 standards of all three systems, including CON-ETP, REC-ETP, and NEG-ETP. According to the simulation, the percentage reduction of the rail potential was 9.14% when the REC-ETP versus the CON-ETP system was 32.99% when the NEG-ETP system compared to the CON-ETP system and 26.25% when the NEG-ETP system versus the REC-ETP system could be seen in this negative resistance converter system, which can reduce the cost of rails and leakage currents in the DC system. It can also be applied to new rail transport.

Keywords: Rail potential; Stray current; Negative resistance converter (NEG); DC railways; Return conductor

1. Introduction

There are two electrical systems used to drive trains, namely the direct current system (DC) and the alternating current system (AC). As for the electricity supply system to drive the electric trains, there are two systems, namely the third rail system and overhead wire system. Which the overhead wire system, there will be a structure of the current feed system above the rails, often used for long-distance train journeys. The third rail system has advantages in terms of visual pollution effects. There is no cluttering power supply structure above the railroad tracks. But there are restrictions on use and safety. This system is often used on subways or mass transit systems. In this research, the focus is on the third rail direct current system due to case studies MRT purple line (North) organized in this.

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Nomenclature

NEG-ETP	Negative resistance converter electric traction power.
CON-ETP	Conventional electric traction power.
REC-ETP	Return conductor electric traction power.
NEG	Negative resistance converter.
FEC	Feeder cable.
SW	Switch unit.
u_r	Voltage of zero-resistance loop.
u_{NEG}	Output voltage of NEG.
u_{FEC}	Voltage across FEC.
u_{SW}	Conducting voltage drop of SW.
u_{rT}	Rail potential of CON-ETP.
u_{rR}	Rail potential of REC-ETP.
u_{rN}	Rail potential of NEG-ETP.
i_{rT}	Stray current of CON-ETP.
i_{rR}	Stray current of REC-ETP.
i_{rN}	Stray current of NEG-ETP.

The traction current flows back to the power substation through the track in DC electric propulsion systems such as electric trains, trams, and mass transit systems causing the rail potential. Part of the reverse current flows to the soil through the running rail. This section is called stray current [1]. In running rails and underground metallic pipes, stray current can cause substantial electrochemical corrosion and when people enter or exit the train, the rail potential might create an electrical shock [2].

However, this paper will focus on the rail potential and stray current reduction in DC electric train system by a new method called NEG-ETP. It is a new method in which additional equipment is installed in the old system as shown in Fig. 1. Whether it is a CON-ETP and a REC-ETP. It is a method of bringing the conductors parallel to the running track [3]. Extra tracks divide the current and reduce the equivalent resistance of running rail. However, installing extension rails and modifying relevant components in an electric train system can often be costly and constraints on cable quantity and cost. If the number of cables is not enough the result of the reduction would be unclear [4]. These two systems are the ones that are currently in use. The new method uses the principle by reducing the rail current that returns on the moving rails by applying zero resistance in a closed circuit [5].

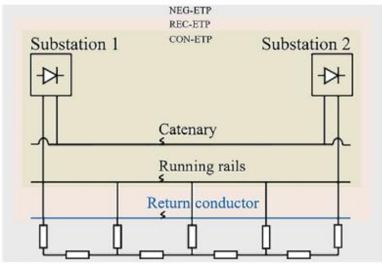

Fig. 1. Diagram of CON-ETP, REC-ETP and NEG-ETP.

The topics of this article are organized as follows: The operation principles and assessment are in-depth analysis in Section 2. Section 3 presents the model of case study. The simulation results and mitigation percentage of rail potential and conclusion are proposed in Section 4 and Section 5, respectively.

2. Operating principles and assessment

The power supply systems of electric traction substations include rail conductors or contact lines, and tracks or running rails, with CON-ETP, REC-ETP, and NEG-ETP layouts available presented in Fig. 1. and separated in Fig. 2. The classical mathematical model for double-side power supply is determined by a model for supplying power to the train, including power supply substation, trains, rail resistance and conductive unit length to make it easier to calculate as shown in Fig. 3, when I_{x1} and I_{x3} are currents flowing in and out at nodes a and c, respectively, and L_1 is the considered length of this section.

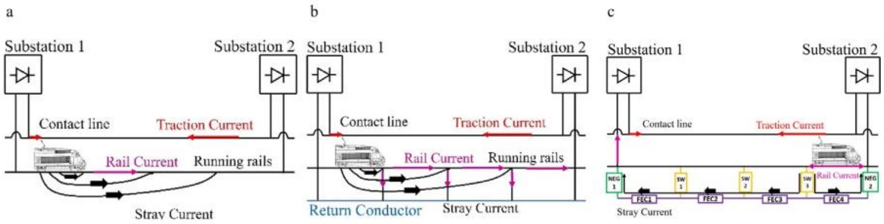

Fig. 2. Operation principles of return current to substations. (a) CON-ETP (b) REC-ETP (c) NEG-ETP.

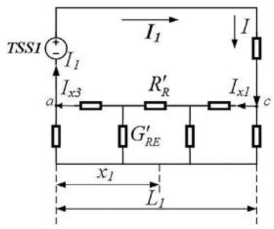

Fig. 3. Classical mathematical model for double-side power supply for calculation between considered nodes.

2.1. Conventional electric traction power system

Fig. 2(a) shows the configuration of CON-ETP as a train travelling between substation 1 and substation 2, traction current is delivered to the train via the overhead wire, which is parallel to the rails. Once the power supplies the electric traction motor on the train, the current will go to the wheel and running rail then back to substation. In addition, the stray current capably flows to the ground and returns to substation [6].

For the CON-ETP operation, the parameters A_k and B_k are obtained in terms of the summation of currents. It would be seen the mathematical model in Fig. 3. If the train moves a distance x_1 from node a to node c for a distance L_1, rail potential, u_{rT}, and stray current, i_{sT}, are computed as follows in Eq. (1) when $\alpha = \sqrt{R'_R G'_{RE}}$

$$\begin{cases} u_{rT(k)} = R_g(A_k e^{x\alpha} + B_k e^{-x\alpha}), \quad 2 \le k \le n \\ i_{sT} = \dfrac{1}{2R_g} \displaystyle\int_0^L \sum_{k=2}^{k=n} \left| u_{rT(k)} \right| dx = \dfrac{u_{rT(k)}}{R_g} \end{cases} \tag{1}$$

According to the $x_1 = 0$ (node a) and $x_1 = L_1$ (node c). Substitution such values in Eq. (1) can be expressed in Eqs. (2) and (3), respectively.

$$I'_R(0) = A_k e^{\alpha(0)} + B_k e^{-\alpha(0)} = A_k + B_k \tag{2}$$

$$I'_T(L_1) = A_k e^{\alpha(L_1)} + B_k e^{-\alpha(L_1)} \tag{3}$$

When $I'_R(0) = I_{x3}$ and $I'_R(L_1) = I_{x1}$ $(B = I_{x3} - A)$. From the above equation, it was found that the variables A_k and B_k which can be calculated according to as follows in Eq. (4):

$$
\begin{aligned}
&A_k e^{\alpha L_1} + (I_{x3} - A_k)e^{-\alpha L_1} = I_{x1} \\
&A_k = \frac{I_{x1} - I_{x3}e^{-\alpha L_1}}{e^{\alpha L_1} - e^{-\alpha L_1}}
\end{aligned} \tag{4}
$$

2.2. Return conductor electric traction power system

Fig. 2(b) shows the configuration of REC-ETP. The parallel rails and the return conductors are connected at the definite distance for example every 5–6 km. The rail currents mostly return to substations through the return conductors [7]. As a result, the amount of rail current leaking to the ground is decreased.

The calculation in REC-ETP can be also calculated from Eq. (1) and considered mathematical model in Fig. 3. However, the model of REC-ETP is slightly different in comparison with CON-ETP with additional nodes of the next sections.

2.3. Negative resistance converter electric traction power system

Fig. 2(c) shows the schematic diagram of NEG-ETP. NEGs, FECs, and SWs are included in the CON-ETP model. During a train running pass SWs in the closed circuit, SWs would be activated, enabling the return current to take a shorter path [8]. The output voltage of NEGs is changed to match the negative equivalent voltage of FECs and SWs that makes the voltage summation in the new closed circuit to be zero. The zero resistance is ideally obtained from the turning-on SWs to NEGs connection.

As illustrated in Fig. 4(a), the NEG is a full-bridge bipolar-switching dc–dc converter with a adaptable tuning output voltage and output resistance. A bidirectional switch, or SW includes a couple IGBTs connected in series with reverse direction illustrated in Fig. 4(b). The model of FEC is configured the parallel of the rail resistors as shown in Fig. 4(c). Therefore, the return current can flow in both direction via NEGs and SWs.

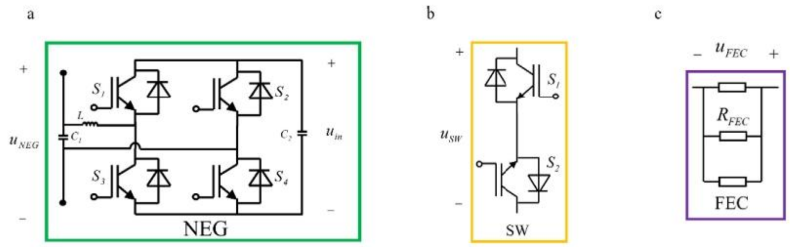

Fig. 4. Power electronic devices connected in NEG-ETP. (a) NEG. (b) SW. (c) FEC.

The mitigation of rail potential and stray current could be obtained by separated the rail to be a section with the specific length. To simplify the case study, the running rails would be separated into four sections, then the output resistances of NEGs are determined in Eqs. (5) and (6). Rail potential, u_{rN} and stray current, i_{sN} in NEG-ETP shown in Fig. 3, are expressed in Eq. (7), where parameters G_k and H_k are derived from the proof of each consideration scope given in variable by applying KVL and KCL calculation.

$$
u_{NEG1} \equiv \begin{cases} -u_{FEC1} - u_{SW1}, & k = 1 \\ -\sum\limits_{j=1}^{j=k-1} u_{FECj} - u_{SW(k-1)}, & 2 \le k \le n \end{cases}
$$

$$
u_{NEG2} = \begin{cases} \sum\limits_{j=k+1}^{j=n} u_{FECj} - u_{SW(k)}, & 1 \le k \le n-1 \\ u_{FEC(n)} - u_{SW(n-1)}, & k = n \end{cases}
$$

$$\text{So } R_{NEG1} = \frac{u_{NEG1}}{i_{NEG1}} \tag{5}$$

$$\text{So } R_{NEG2} = \frac{u_{NEG2}}{i_{NEG2}} \tag{6}$$

$$R_{NEG1} = \begin{cases} -R_{FECj} - R_{SW1}, & k = 1 \\ -\sum_{j=1}^{j=k-1} R_{FECj} - R_{SW(k-1)} & 2 \le k \le n \end{cases}$$

$$R_{NEG2} = \begin{cases} -\sum_{j=k+1}^{j=n} R_{FECj} - R_{SW(k)}, & 1 \le k \le n-1 \\ -R_{FEC(n)} - R_{SW(n-1)}, & k = n \end{cases}$$

$$\begin{cases} u_{rN(k)} = R_g(G_k e^{x\alpha} + H_k e^{-x\alpha}), \quad 1 \le k \le n \\ i_{sN} = \dfrac{1}{2R_g} \displaystyle\int_0^L \sum_{k=1}^{k=n} \left| u_{rN(k)} \right| dx = \dfrac{u_{rN(k)}}{R_g} \end{cases} \tag{7}$$

2.4. Assessment stray current for the MRT purple line

The stray current offered as a reference value for electric trains should be no more than 2.5 mA/m/track to assess stray current according to EN 50122-1 and EN 50122-2 [9,10], however the runway stray current measurement is a concern. Only the influence caused by stray current may be measured, which is essentially impossible. This will be the rail's own potential. The rail potential may be computed using EN 50122-2 determined in Eq. (8).

$$U_{RE} = 0.5 \times I_{tr} \times R_c \times \left(1 - e^{-\left(\frac{L}{L_c}\right)}\right) \tag{8}$$

where, U_{RE} is the voltage value along the length (V), I_{tr} is the mean return current circuit of the section under consideration during peak load (A), R_C is the resistance characteristics of the rails per unit length (Ω/km), L is the length of interest to consider for the route (km), L_C is the length of the track (km). Which values R_C and L_C can be obtained from Eqs. (9) and (10)

$$R_C = \sqrt{\frac{R'_R}{G'_{RE}}} \tag{9}$$

$$L_C = \frac{1}{\sqrt{R'_R \times G'_{RE}}} \tag{10}$$

where, R'_R is the rail resistance per unit length (Ω/km), G'_{RE} is the conductivity per unit length between rail and ground (S/km).

3. Model of case study

The flow chart to evaluate the rail potential is presented in Fig. 5. Firstly, the detection of train location is obtained by the train movement calculation with obtaining the train position, train speed and train power. Secondly, REC-ETP and NEG-ETP calculate the rail potential for rail-section and CON-ETP is also calculated the rail potential. If a train travels to the end of the track, then the simulation will also be end. A train simulation program is carried out in MATLAB using a model of the train in MRT purple line for determining the rail potential. It includes 16 passenger stations and 10 traction substations. The train and system information of the MRT purple line (North) are presented in Table 1. and the station location information is shown in Table 2. The train is electrified through the third rail with a rated voltage of 750 V.

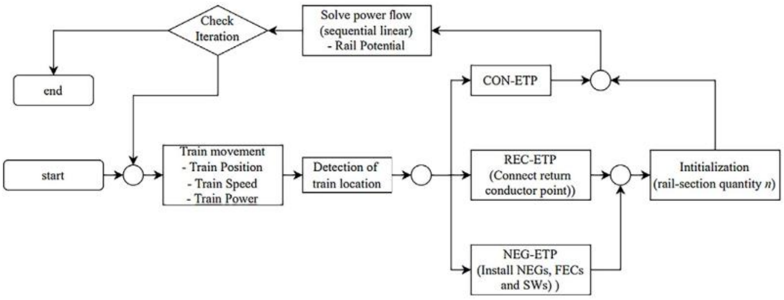

Fig. 5. Rail potential evaluation procedure: CON-ETP, REC-ETP and NEG-ETP.

Table 1. Train and system information of the MRT purple line (North) for simulation.

Specific data	Information	Value	Unit
Train parameters			
Movement feature	Max. speed	80	km/h
	Max. acceleration	1.2	m/s^2
	Max. deceleration	0.9	m/s^2
Weight	Train mass	135	ton
	Passenger mass	75	ton
Tractive effort curve	Maximum tractive effort	228.8	N
	Maximum braking effort	168.8	N
Efficiency	Motor power factor	0.86	–
Auxiliary power	Constant load	270	kW
Train resistance			
3rd Rail resistance		0.007	Ω/km
Track resistance		0.0175	Ω/km
Earth resistance		12	Ω
Rail-to-earth conductance		2	S/km
Substation parameter			
Voltage no-load		750	V
Short-circuit capacity		50	MW

4. Simulation results

4.1. Assessment stray current for the MRT purple line (North)

The stray current assessment for the MRT Purple Line (North) is calculated from (8), (9) and (10) mentioned above. It was found a rail potential of 48.97 V and a stray current of 0.0979 mA/m for a rating of 7106.413 A and compared with the simulation result of a single train movement as shown in Fig. 5, as shown in Table 3.

From Table 3, it is found that the rail potential is different. As a result of a single train simulation, there is stray current accumulated in the ground that flows back into the propulsion substation. However, both obtained rail potentials are standardized to the EN 50122-2 standard, i.e., the allowable voltage is no more than 120 V, and it is recommended that no damage to the railway up to 25 years, if stray current per unit is below 2.5 mA/m. The simulation results of CON-ETP, REC-ETP and NEG-ETP systems can be described in Figs. 6–8, respectively.

Table 2. Station location information.

Station code	Substation code	Station name	Station position (km)
PP01	TSS01	Khlong Bang Phai	0.00
PP02	TSS02	Talad Bang Yai	1.27
PP03	TSS03	Sam Yaek Bang Yai	2.83
PP04	–	Bang Phlu	4.40
PP05	TSS04	Bang Rak Yai	5.60
PP06	–	Bang Rak Noi Tha It	6.85
PP07	TSS05	Sai Ma	8.10
PP08	–	Phra Nang Klao Bridge	9.57
PP09	TSS06	Yaek Nonthaburi 1	11.20
PP10	–	Bang Krasor	12.46
PP11	TSS07	Nonthaburi Civic Center	13.36
PP12	–	Ministry of Public Health	15.15
PP13	TSS08	Yaek Tiwanon	16.35
PP14	TSS09	Wong Sawang	18.07
PP15	TSS010	Bang Son	19.36
PP16	–	Tao Poon	20.94

Table 3. Comparison of stray current assessment results during single train motion simulations with rail potential calculations obtained from grounding models according to EN 50122-2.

Assessment procedure	Rail potential (V)
Simulation result of a single train movement	76.38
Calculation of rail potential according to EN 50122-2	48.97

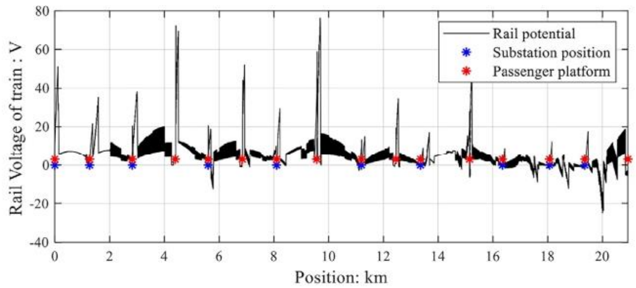

Fig. 6. Rail potential of CON-ETP.

4.2. *Conventional electric traction power system*

Fig. 6 shows the rail potential of the CON-ETP system. At the passenger station 8 (PP08) located between substation 5 and substation 6 (TSS05-TSS06), the maximum rail potential of 76.38 V is obtained. Considering the other peaks of rail potential, they are occurred at passenger station located between substations during the train operation in accelerating mode. The rail potential would reduce when the train running in cursing and coasting modes.

4.3. *Return conductor electric traction power system*

As a case study, the connected points of the return conductor and the running rail are located at of 0, 5, 10, 15, 19.36 and 20.94 km. The maximum rail potential of 69.40 V is obtained at the passenger station 10 (PP10) located halfway between substation 6 and 7 (TSS06-TSS07) as shown in Fig. 7. It is pointed out that the peak rail

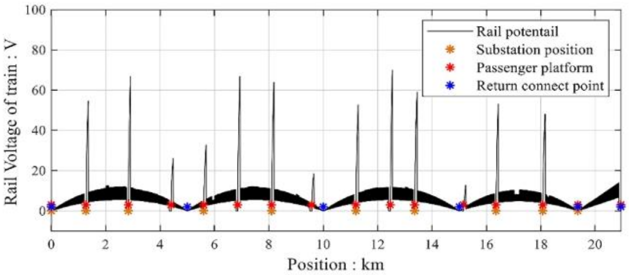

Fig. 7. Rail potential of REC-ETP.

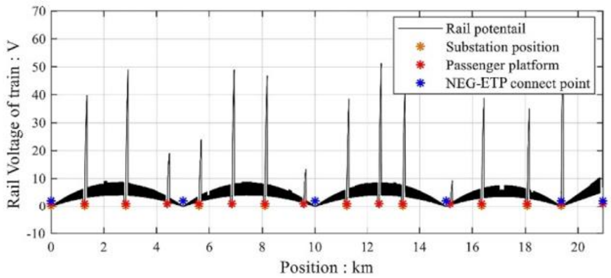

Fig. 8. Rail potential of NEG-ETP.

potential occurred at each passenger station located around middle between the connected points is higher than the passenger station located near the connected point. The maximum rail potential of REC-ETP system is lower than that of CON-ETP system of 9.14%.

4.4. Negative resistance converter electric traction power system

The connected points of the return conductor and the running rail are located at same position as the REC-ETP system. The rail potential of the NEG-ETP system is shown in Fig. 8. At passenger station 10 (PP010) located halfway between substation 6 and 7 (TSS06-TSS07), the maximum rail potential of 51.18 V is obtained. The peak rail potential occurred at each passenger station located around middle between the connected points is higher than the passenger station located near the connected point similar with the REC-ETP system, but a bit lower. The maximum rail potential of the NEG-ETP and the REC-ETP are reduced by 32.99% and 9.14% in comparison with the CON-ETP as shown in Table 4. Regarding the maximum rail potential evaluation, the NEG-ETP is lower than the REC-ETP by 26.25%.

Table 4. Percentage reduction of rail potential.

System	Rail potential (V)	Percentage decrease (%)
CON-ETP (Base case)	76.38	–
REC-ETP	69.40	9.14
NEG-ETP	51.18	32.99

5. Conclusion

In this paper, NEG-ETP is a new concept developed by installing additional power electronic equipment, there is no need to modify the original structure of the railway infrastructure, recommended in the urban rail transportation to mitigate rail potential and stray current. The configuration of NEG-ETP is separated into several rail-sections, with non-train rail-sections having zero rail current. From proposed method, this was applied to the mass rapid transit system namely MRT purple line (North), in Thailand simulated by the MATLAB/M-file. This was pointed out that rail potential and stray current would be evidently mitigated by NEG-ETP as a percentage reduction compared to CON-ETP and REC-ETP is 9.14% and 32.99% respectively.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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