1.Aran Prakobsant[1], 2.Dhidik Prastiyanto[2], 3.Chonlatee Photong[1,*]

Faculty of Engineering, Mahasarakham University, Thailand, *corresponding author (1)
Department of Electrical Engineering, Universitas Negeri Semarang, Indonesia (2)

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Optimum Power-Weight Ratio for Dual 3-Phase Induction Motor Drives for Regenerative Power Maximization

Abstract. *Dual electric motor drives inherently provide easier torque control, better acceleration, and robust handling. However, they have some drawbacks related to high weight, cost and complexity, which would need more research to eliminate these issues. This paper proposes the development of analytical and practical models to determine the optimum power-weight ratio for electric motors used in the dual motor drive systems in order to achieve maximum regenerative power generation during braking. The case studies of commonly used 3-phase induction motors for electric automotive applications were observed with the operating power rate in the range between 0.18 – 375 kW. The specifications of the motors of 3 manufacturers: General Electric, Siemens, and ABB, were used for the model development and analysis. The analytical results showed that the maximum regenerative power could be achieved only when two electric motors were identical with the same power-weight ratio. Although using the same rated power of the motors, different manufacturers provided significantly different amounts of maximum regenerative power. Lighter power load rating of the motors trended to generate higher regenerative braking power reflected by the regenerative power of 138.2-226.9 kW (36.9-60.5%) at high load of 375 kW, 78.5-128.3 kW (41.9-68.4%) at medium load of 187.5 kW and 18.9-31.5 kW (50.4-84.0%) at light load of 37.5kW. Low RPM speed motors trended to generate higher regenerative power than high RPM speed motors, reflected by the generated power of 26.4-226.9 kW for 1,000RPM compared to 18.9-209.2 kW and 17.9-210.7 of 1,500 RPM and 3,000 RPM. The power-weight ratio (kW/kg) lower than approximately 0.08 provided almost linear increasing in of maximum regenerative power proportional to the increasing rate of power-weight ratio. In turn, the regenerative power could be generated exponentially for power-weight ratio became over 0.08 – 0.12 dependent on RPM speed specification and fabrication technology of each manufacturer. These results could be the critical parameters for the optimum design for the electric automotive applications based dual motor drive approach.*

Streszczenie. *Podwójne napędy silników elektrycznych z natury zapewniają łatwiejszą kontrolę momentu obrotowego, lepsze przyspieszenie i niezawodne prowadzenie. Mają jednak pewne wady związane z dużą wagą, kosztem i złożonością, co wymagałoby dalszych badań w celu wyeliminowania tych problemów. W artykule zaproponowano opracowanie modeli analitycznych i praktycznych w celu określenia optymalnego stosunku mocy do masy silników elektrycznych stosowanych w dwusilnikowych układach napędowych, w celu uzyskania maksymalnej generacji mocy regeneracyjnej podczas hamowania. Zaobserwowano studia przypadków powszechnie stosowanych 3-fazowych silników indukcyjnych do elektrycznych zastosowań motoryzacyjnych o mocy roboczej w zakresie 0,18 – 375 kW. Do opracowania i analizy modelu wykorzystano specyfikacje silników 3 producentów: General Electric, Siemens i ABB. Wyniki analiz wykazały, że maksymalną moc regeneracyjną można było uzyskać tylko wtedy, gdy dwa silniki elektryczne były identyczne i miały ten sam stosunek mocy do masy. Pomimo stosowania tej samej mocy znamionowej silników, różni producenci zapewniali znacząco różną wielkość maksymalnej mocy regeneracyjnej. Mniejsza moc znamionowa silników wykazywała tendencję do generowania wyższej mocy hamowania regeneracyjnego odzwierciedlonej przez moc regeneracyjną 138,2–226,9 kW (36,9–60,5%) przy dużym obciążeniu 375 kW, 78,5–128,3 kW (41,9–68,4%) przy średnim obciążeniu 187,5 kW i 18,9-31,5 kW (50,4-84,0%) przy lekkim obciążeniu 37,5 kW. Silniki o niskich obrotach generują wyższą moc regeneracyjną niż silniki o wysokich obrotach, co znajduje odzwierciedlenie w generowanej mocy 26,4–226,9 kW przy 1000 obr./min w porównaniu z 18,9–209,2 kW i 17,9–210,7 przy 1500 obr./min i 3000 obr./min. Stosunek mocy do masy (kW/kg) niższy od około 0,08 zapewniał niemal liniowy wzrost maksymalnej mocy regeneracyjnej proporcjonalnie do tempa wzrostu stosunku mocy do masy. Z kolei moc regeneracyjna generowana wykładniczo dla stosunku mocy do masy przekraczała 0,08 – 0,12, w zależności od specyfikacji prędkości obrotowej i technologii produkcji każdego producenta. Wyniki te mogą stanowić krytyczne parametry dla optymalnego projektu podejścia z podwójnym napędem silnikowym do zastosowań w motoryzacji elektrycznej.* (***Optymalny stosunek mocy do masy dla podwójnych 3-fazowych napędów silników indukcyjnych w celu maksymalizacji mocy regeneracyjnej***)

Keywords: power to weight ratio, motor weight, dual motor drives, regenerative power, regenerative braking, electric vehicles
Słowa kluczowe: stosunek mocy do masy, masa silnika, napędy dwusilnikowe, moc regeneracyjna, hamowanie regeneracyjne, pojazdy elektryczne

Introduction

Dual electric motor drives have their unique characteristics and advantages related to easier for torque handling, better acceleration, and more robustness that could not be achieved by other drive systems [1]-[3]. However, they have some common challenges in high weight, cost, and complexity when used them for electric automotive applications [4]-[5]. In [6]-[10] proposed methods to decrease weight of electric motors while maximizing regenerative power production focusing on implementation of optimization controls and physical feature rearrangements. In [11], the possibility of managing two different ratings of motor powers and capability to generate electricity under both constant running and braking conditions has been proposed while most other research works utilized two identical electric motors for dual motor drive systems for structure and control simplicity [12]-[17] but could not achieve generate power for both during running and braking. However, there is no research that considered the optimum ratio between the power and weight of electric motors for the dual motor drives before.

This paper proposed the development the theoretical-practical models and analysis for optimum power-to-weight ratio of the 3-phase induction motors in dual motor drives. The specifications of commercial electric motors selected from 3 manufacturers were utilized to complete the models, as well as, to validate the proposed analysis.

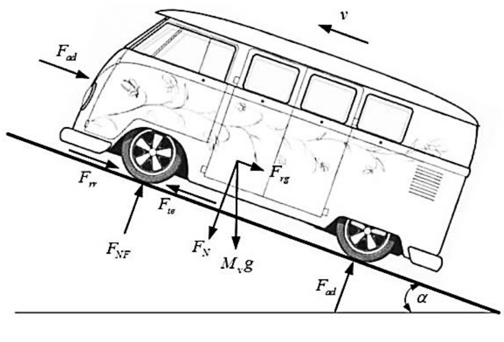


Fig. 1. Forces on a moving vehicle [17].

Analytical Model Development

A. *Theoretical model Development*

The models used for analyzing the optimum power-weight of motors for dual electric motor drives were formulated from Fig. 1 [17] and equations (1)-(3); where definition of parameters, how to find the most suitable value of each parameter, and how to calculate can be found in [11].

(1) $F_{te} = \mu_{rr}mgcos(\alpha) + \frac{1}{2}\rho c_d A v^2 + mgsin(\alpha) + ma$

(2) $P_{te} = F_{te}v$

substituting (2) into (1), yields (3):

(3) $P_{te} = \mu_{rr}mgvcos(\alpha) + \frac{1}{2}\rho c_d A v^3 + mgvsin(\alpha) + mva$

Under braking conditions, when assuming all amount of the power caused the reaction of motors (P_{te}) is fully transferred to regenerative power (G_{te}) without any losses, the regenerative power (G_{te}) should be therefore equal to -P_{te}. This should be the situation when the car is eventually stopped. Hence, a =(0-v)/t) and (4) can be obtained, where t is the braking time (in second).

(4) $G_{te} = \left[\frac{v}{t} - \mu_{rr}gcos(\alpha) - gsin(\alpha)\right] vm - [\frac{1}{2}\rho c_d A v^3]$

When considering only the effect of the 3-phase induction motors M_1 and M_2 with the rated power of P_{m1} and P_{m2}, and weight of m_{m1} and m_{m2}, respectively; thus, the last term of (4) should be neglected and thus (4) could be simplified as (5).

(5) $G_{tm} = \left[\frac{v}{t} - \mu_{rr}gvcos(\alpha) - gvsin(\alpha)\right] (m_{m1} + m_{m2})$

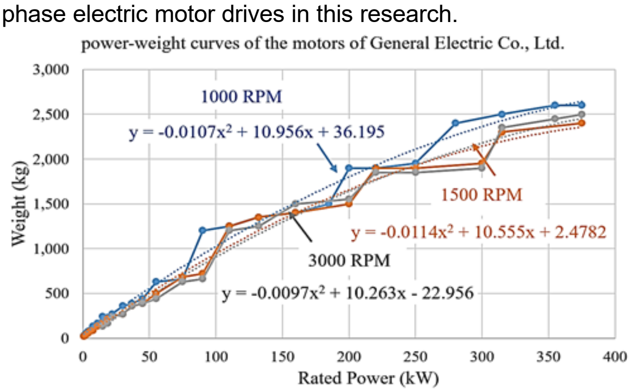
The equation (5) was used to study and analyze the optimum power-weight ratio for the two electric motors for the dual 3-phase electric motor drive.

B. *Practical Model Development*

The critical specification data of the 3-phase induction motors in terms of rated power, speed, and weight collected from 3 commercial motor manufacturers: General Electric (GE) Co., Ltd., SIEMENS Co., Ltd. and ABB Co., Ltd. were selected and used for this study [18]-[20]. Their product specifications for the rated speed ranges of 1,000, 1,500 and 3,000 round per minute (RPM) are shown in Table 1-3, which w

ere used to fit the curves and estimated equations as results shown

in Fig. 2. According to Fig.2, the motor power rating in the range between 0.18 – 375 kW was investigated. This power range is the range currently used for commercial electric automotive applications nowadays. The curves were estimated by using a second order polynomial equation (y = ax^2 + bx + c) for each particular power-weight specification of the manufacturer. The resultant equations (6)-(14) are listed in Table 4. These equations were used to develop practical mathematic models for the study of the optimum power-weight ratio of the motors for the dual 3-phase electric motor drives in this research.



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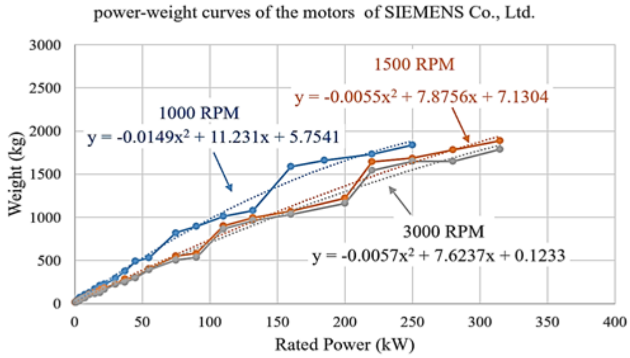

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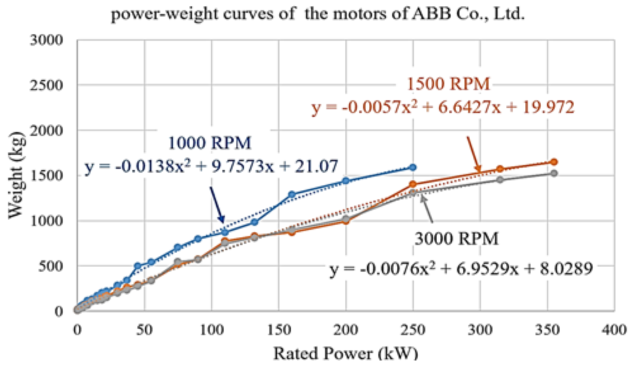


(c)

Fig. 2. Power-weight characteristic curves of 3-phase induction motors of (a) General Electric, (b) SIEMENS, and (c) ABB Co., Ltd.

Table 1. Estimated power-weight characteristics curves of the 3-phase induction motors of each manufacturer (Genernal Electric Co., Ltd, SIEMENS Co., Ltd, and ABB Co., Ltd.)

Manufacturer	Speed Range (rpm)	Estimated equation for power-weight characteristic curves *m*: weight (in kg); *P*: power (in kW)
General Electric (GE)	1,000	m = -0.0107P^2 + 10.956P + 36.195 (6)
	1,500	m = -0.0114P^2 + 10.555P + 2.4782 (7)
	3,000	m = -0.0097P^2 + 10.263P + 8.956 (8)
SIEMENS	1,000	m = -0.0149P^2 + 11.231P + 5.7541 (9)
	1,500	m = -0.0055P^2 + 7.8756P + 7.1304 (10)
	3,000	m = -0.0057P^2 + 7.6237P + 0.1233 (11)
ABB	1,000	m = -0.0138P^2 + 9.7573P + 21.070 (12)
	1,500	m = -0.0057P^2 + 6.6427P + 19.972 (13)
	3,000	m = -0.0076P^2 + 6.9529P + 8.0289 (14)

Results

There were 3 test scenarios for this study. The first test was to investigate the regenerative power under braking conditions for different power rating and weight of the motors when the motors were operating at high load of 375 kW, medium load of 187.5 kW and light load of 37.5 kW. The second test was to observe the maximum regenerative power for each motor power rating between 1 – 375 kW. The last test was to study the optimum power-weight ratio of the motors for regenerative power generation during the braking. Table 5 shows the test parameters for the sample vehicles of 750 kg with normal dry concrete road with clear environment. An additional explanation of each parameter can be found in [11].

Table 1. The specification of 3-phase induction motors of General Electric Co., Ltd. [18]

Speed: 1,000 RPM			Speed:1,500 RPM			Speed: 3,000 RPM		
Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)
0.75	24	965	0.75	17	1440	0.75	17	2850
1.5	37	970	1.5	24	1450	1.5	21	2865
2.2	50	975	2.2	37	1450	2.2	24	2890
3.7	72	975	3.7	50	1465	3.7	50	2930
5.5	84	980	5.5	72	1470	5.5	65	2935
7.5	135	980	7.5	84	1470	7.5	72	2940
11	163	980	11	135	1470	11	121	2950
15	238	985	15	163	1475	15	135	2955
18.5	228	985	18.5	215	1480	18.5	163	2950
22	270	985	22	238	1475	22	238	2960
30	360	985	30	270	1475	30	270	2960
37	385	980	37	360	1480	37	360	2970
45	440	985	45	385	1480	45	385	2975
55	630	980	55	500	1475	55	440	2965
75	660	990	75	680	1480	75	630	2970
90	1200	990	90	720	1480	90	660	2970
110	1250	990	110	1250	1485	110	1200	2970
132	1350	985	132	1350	1485	132	1250	2975
160	1400	985	160	1400	1480	160	1500	2970
185	1500	985	200	1500	1480	200	1550	2790
200	1900	985	220	1900	1480	220	1850	2970
220	1900	985	250	1900	1480	250	1850	2970
250	1950	985	300	1950	1485	300	1900	2970
280	2400	985	315	2300	1485	315	2350	2975
315	2500	985	375	2400	1485	355	2450	2975
355	2600	985				375	2500	2975
375	2600	985						

Table 2. The specification of 3-phase induction motors of SIEMENS Co., Ltd. [19]

Speed: 1,000 RPM			Speed:1,500 RPM			Speed: 3,000 RPM		
Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)
0.55	16	885	0.55	14	1390	0.75	14	2845
0.75	20	910	0.75	15	1380	1.1	15	2840
1.1	23	910	1.1	21	1390	1.5	22	2840
1.5	31	920	1.5	23	1390	2.2	24	2840
2.2	40	935	2.2	31	1410	3	33	2860
3	56	960	3	33	1410	4	38	2880
4	68	960	4	44	1435	5.5	58	2900
5.5	75	960	5.5	61	1440	7.5	63	2900
7.5	104	970	7.5	71	1440	11	105	2930
11	127	970	11	110	1460	15	115	2930
15	167	970	15	132	1460	18.5	128	2930
18.5	210	980	18.5	164	1470	22	165	2940
22	223	980	22	180	1470	30	225	2950
30	290	980	30	225	1470	37	246	2950
37	375	980	37	285	1475	45	296	2960
45	492	980	45	305	1475	55	390	2965
55	530	980	55	400	1480	75	504	2970
75	820	989	75	553	1480	90	536	2970
90	895	989	90	582	1480	110	865	2975
110	1010	989	110	900	1480	132	960	2975
132	1080	989	132	995	1480	160	1035	2975
160	1590	989	160	1070	1480	200	1160	2975
185	1660	989	200	1220	1480	220	1545	2987
220	1730	989	220	1645	1490	250	1650	2987
250	1835	989	250	1685	1490	280	1650	2987
			280	1780	1490	315	1790	2987
			315	1890	1490			

Table 3. The specification of 3-phase induction motors of ABB Co., Ltd. [20]

Speed: 1,000 RPM			Speed:1,500 RPM			Speed: 3,000 RPM		
Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)	Output (kW)	Weight (kg)	Speed (rpm)
0.18	9	905	0.25	9	1424	0.37	9	2820
0.25	10	920	0.37	10	1418	0.55	10	2831
0.37	14	916	0.55	15	1441	0.75	14	2843
0.55	19	932	0.75	18	1446	1.1	15	2860
0.75	22	951	1.1	22	1447	1.5	21	2887

1.1	25	936	1.5	24	1444	2.2	24	2894
1.5	31	957	2.2	31	1445	3	32	2919
3	57	966	3	35	1443	4	36	2916
4	65	964	4	41	1442	5.5	56	2921
5.5	79	964	5.5	59	1457	7.5	60	2916
7.5	114	974	7.5	70	1457	11	103	2931
11	134	971	11	111	1466	15	116	2938
15	169	971	15	126	1468	18.5	124	2939
18.5	205	978	18.5	156	1470	22	151	2943
22	219	978	22	169	1472	30	198	2957
30	284	987	30	222	1476	37	229	2951
37	337	986	37	265	1479	45	275	2962
45	500	990	45	292	1481	55	335	2965
55	540	990	55	340	1480	75	546	2975
75	705	992	75	515	1484	90	570	2976
90	800	992	90	575	1481	110	750	2981
110	870	992	110	775	1488	132	810	2978
132	980	992	132	830	1487	160	900	2981
160	1290	992	160	870	1487	200	1020	2979
200	1440	992	200	995	1486	250	1310	2983
250	1590	991	250	1400	1488	315	1450	2980
			315	1570	1488	355	1520	2983
			355	1650	1487			

Table 5. Test parameters in this study and their values

Parameter	Description	Value
Weight of car	Total weight except motors (in kg)	750
friction coefficient (μ_{rr})	paved/concrete roads with fair conditions; dry	0.02
climbing coefficient (c_d)	general car	0.3
car cross-section area (A)	A=width of 0.7x height of 1.2 (in m^2)	0.84
Air density (ρ)	Air density (in kg/m^3)	1.225
Slope angle (α)	Non-slope $\alpha = 0^o$ (flat road) slope $\alpha = -15^o$ (very steep road) [21]	$0 - 15^o$ (0-25%)
Velocity (v)	See Fig.3 [22] (in km/h)	40-110
Braking time (t)	See Fig.3 [22] (in m equiv.) *a= 5.0-7.0 m/s^2	9 - 67
gravity of earth (g)	Average gravity of earth	9.807

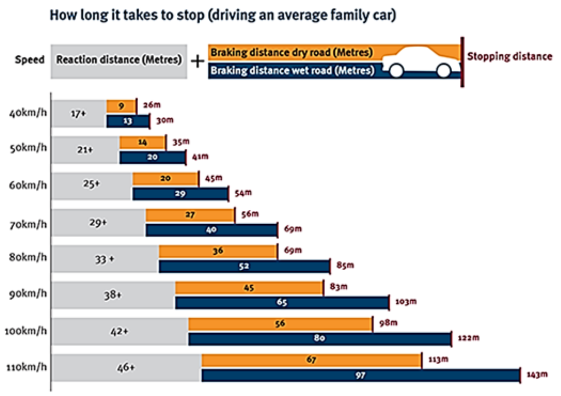


Fig. 3. Braking distances for different driving speed [22]

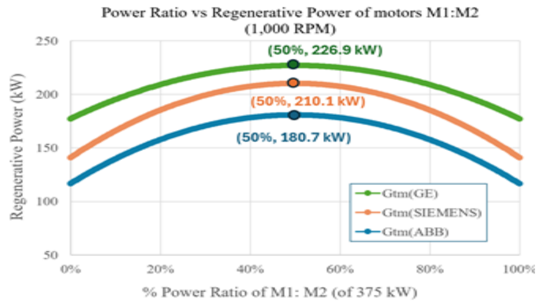
A. Test Results of Regenerative Power Generation under Braking with Different Motor Power and Load Conditions

The investigation of the amount of generated regenerative power obtained from different motor power ratings and load conditions was conducted. From Table 4, using $P_{te}(m_{m1}+m_{m2})$ = 375kW; varying $P_{m1}:P_{m2}$ as 0:375kW to 375:0kW when μ_{rr}=0.02. Set $\alpha = 0^o$ for a flat road, average velocity (v) of 19.44 m/s (70km/h) and t=27/5.0=5.4 s. Apply all the values to (5), the results were obtained as (15) and Fig.4-6.

(16) $$G_{te} = \left[\frac{19.44^2}{5.4} - (0.02)(9.807)(19.44)\cos(0) - (9.807)(19.44)\sin(0)\right](m_{m1} + m_{m2})$$

$$G_{te} = 66.17(m_{m1} + m_{m2})$$

a)



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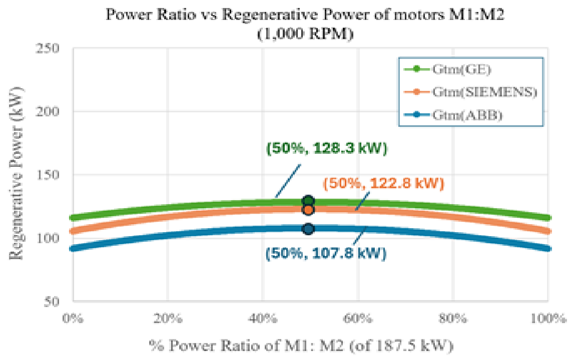

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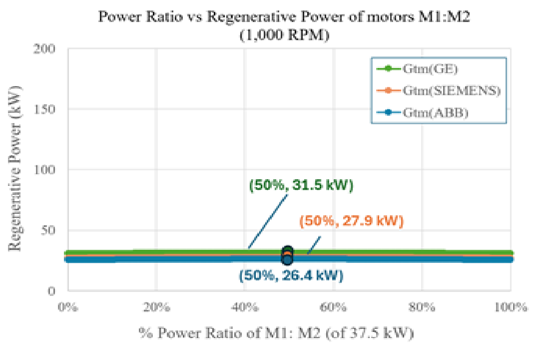
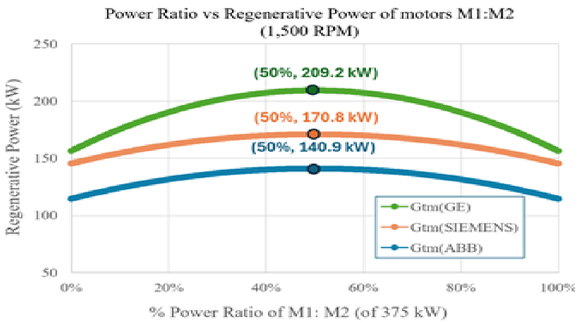


Fig. 4. Rated power vs regenerative power for the 1,000 RPM motors from 3 manufacturers: GE, SIEMENS and ABB at: (a) high load of 375kW; (b) half load of 187.5kW and (c) 10% load (37.5kW)

a)



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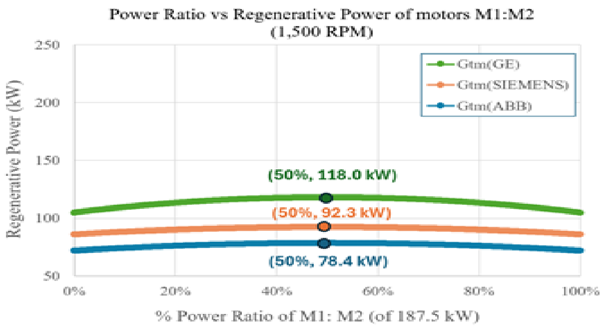

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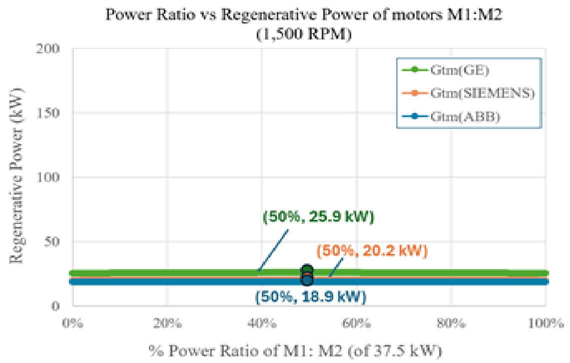
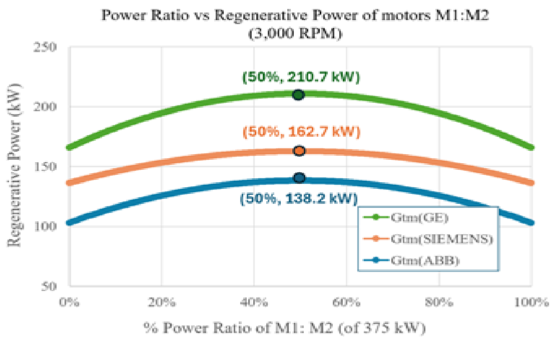


Fig. 5. Rated power vs regenerative power for the 1,500 RPM motors from 3 manufacturers: GE, SIEMENS and ABB at: (a) high load of 375kW; (b) half load of 187.5kW and (c) 10% load (37.5kW)

a)



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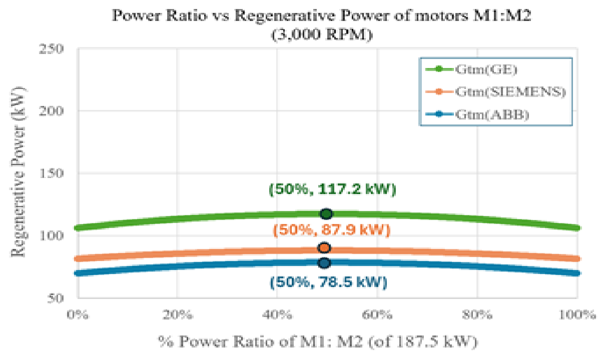

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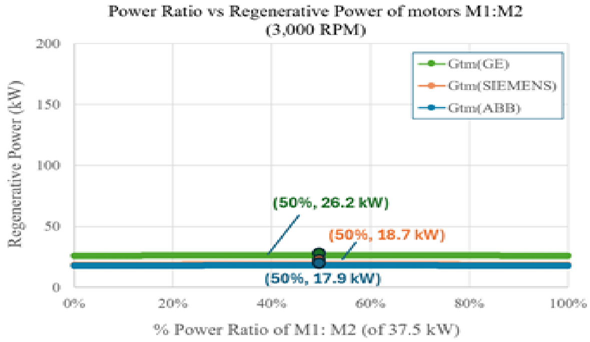


Fig. 6. Rated power vs regenerative power for the 3,000 RPM motors from 3 manufacturers: GE, SIEMENS and ABB at: (a) high load of 375kW; (b) half load of 187.5kW and (c) 10% load (37.5kW)

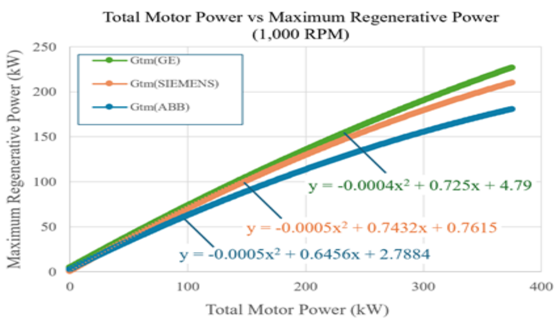
It can be seen from Fig. 4- 6 that the maximum regenerative power under braking for dual motor drives could be achieved only when both electric motors of the system were identical with the same power-weight ratio. Different manufacturers offered notably different maximum regenerative power even when the motors had the same rated power. The regenerative power of 138.2-226.9 kW at high load of 375 kW, 78.5-128.3 kW at medium load of 187.5 kW, and 18.9-31.5 kW at light load of 37.5 kW illustrates the trend of the motors producing higher regenerative braking power when their power load rating is lower; reflected by approximately 50.4 – 84.0% for light load of 37.5 kW, 41.9-68.4% for medium load of 187.5 kW and 36.9-60.5% for high load of 375 kW. In other words, even larger amounts of power regeneration could achieve with higher motor power ratings but, in fact, that amounts of power were significantly lower than lower motor power ratings with an approximately decreasing rate of 0.4-0.7% for every 10kW increase of motor power.

Since the generated power for low RPM speed motors is 26.4–226.9 kW at 1,000 RPM, it is higher than the generated power for high RPM speed motors (18.9–209.2 kW and 17.9–210.7 kW at 1,500 RPM and 3,000 RPM).

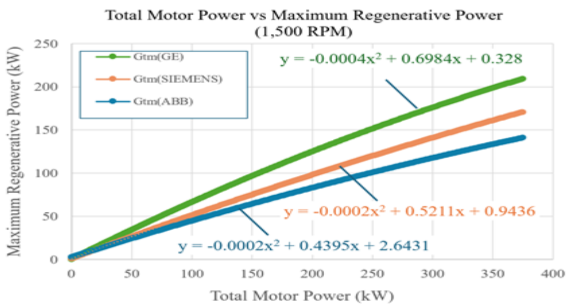
B. Test Results of the Maximum Regenerative Power for each Motor Power Rating

According to the results in Section *A.*, where the maximum regenerative power under braking could be achieved when both dual motors had the same power-weight ratio. In this test, the total rated motor power was set between 1- 375 kW and the maximum possible regenerative power for each rated motor power was observed. The test results are presented in Fig.7. It is clearly seen that the maximum regenerative power increased, almost linearly increased, which the increase of the total motor power rate with the increasing rate of 0.65-0.73, 0.44-0.70, and 0.46-0.68 kW per kW for 1,000, 1,500 and 3,000 RPM motor structure. The 1,000 RPM motor could achieve the highest power regeneration for this study.

a)



b)



c)

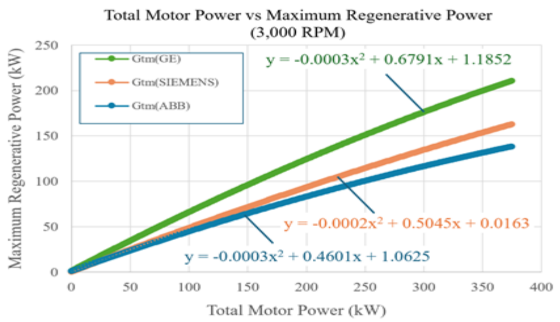
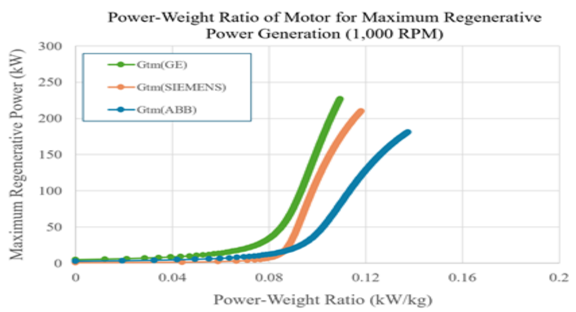
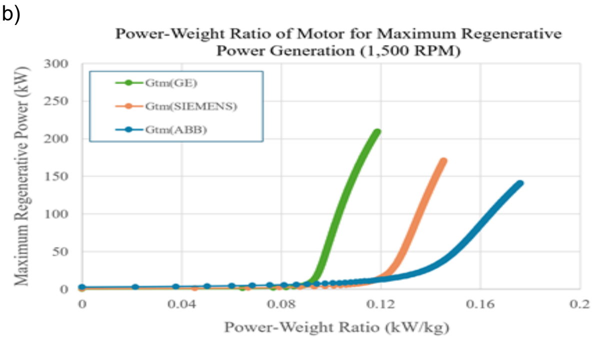


Fig. 7. The plots of total motor power vs maximum regenerative power when using identical features from 3 manufacturers: GE, SIEMENS and ABB for dual drive system with: (a) 1,000 RPM; (b) 1,500 RPM and (c) 3,000 RPM specification.

a)



b)



C(

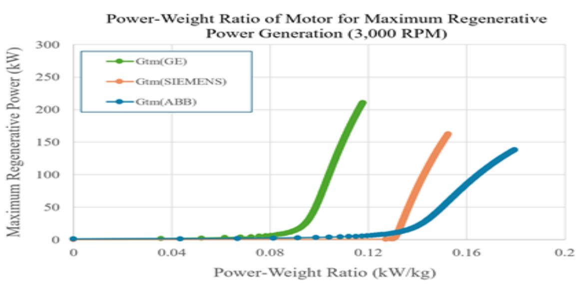


Fig. 8. The plots of power-weight ratio vs maximum regenerative power when using identical features from 3 manufacturers: GE, SIEMENS and ABB for dual drive system with: (a) 1,000 RPM; (b) 1,500 RPM and (c) 3,000 RPM specification.

C. Test Results of the Optimum Power-Weight Ratio of the Motors for Regenerative Power Generation during Braking

In this test, the maximum regenerative power generation during braking with respect to the power-weight ratio of the dual motors was examined and evaluated. The test results obtained from the mathematical models when applying values from Table 2-5 and equation (15) when m_{m1} and m_{m2} were the same are shown in Fig.8. The regenerative power increased linearly with the increase of the power-weight ratio (kW/kg) when the power-weight ratio was relatively lower than 0.08. On the other hand, the regenerative power increased exponentially after the power-weight ratio became over 0.08 – 0.12. The increasing rate and the fast change of the curves was dependent on the RPM specification and fabrication technology of each manufacturer.

Conclusions

This paper proposed development of analytical models for the study of optimum power-weight ratio of 3-phase induction motors of a dual electric motor drives to achieve maximum regenerative power generation during braking. The theoretical model was firstly developed following by the practical models by using the specific data from 3 commercial motor manufacturers (Gneral Electric, SIEMENS, and ABB). The analytical models with power range of 0-375kW were then used for the study. The research results showed that the maximum regenerative power could be achieved only when the motors had same power-weight ratio. Larger motor power ratings (375kW) generated higher regenerative power (138.2-226.9 kW) but, in turn, provided less conversion efficiency (36.9-60.5%) compared to lower motor power ratings (50.4-84.0%). Low-RPM speed motors provided higher regenerative power than high-RPM speed motors. Regenerative power linearly increase with the increasing rate of power-weight ratio of the electric motors when power-weight ratio less than 0.08. With power-weight ratio greater than the range of 0.08-0.12, the generated regenerative power exponentially increased and reached their higest values at the power-weight ratio of upto 0.20. These results are crucial for the optimum power-weight design when the dual electric motor drives are used.

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Authors: *Aran Prakobsant. aran.pr@ku.th Mahasarakham University, Thailand, Dhidik Prastiyanto. dhidik.prastiyanto@mail.unnes.ac.id Universitas Negeri Semarang, Indonesia, and Chonlatee Photong. chonlatee.p@msu.ac.th Mahasarakham University, Thailand.*

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